

# Short Baseline Oscillations

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# Outline

- Introduction
- What are short baseline oscillations ( $L/E \sim 1$ )
- LSND  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  Oscillation Results
- MiniBooNE  $\nu_\mu \rightarrow \nu_e$  Oscillation Search
- MiniBooNE  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  Oscillation Search (**50% more data**)
- Other  $L/E \sim 1$  results and fits to the World Neutrino & Antineutrino Data
- Testing LSND/MiniBooNE Signals with Future Experiments
- Conclusion

# Neutrino Oscillations

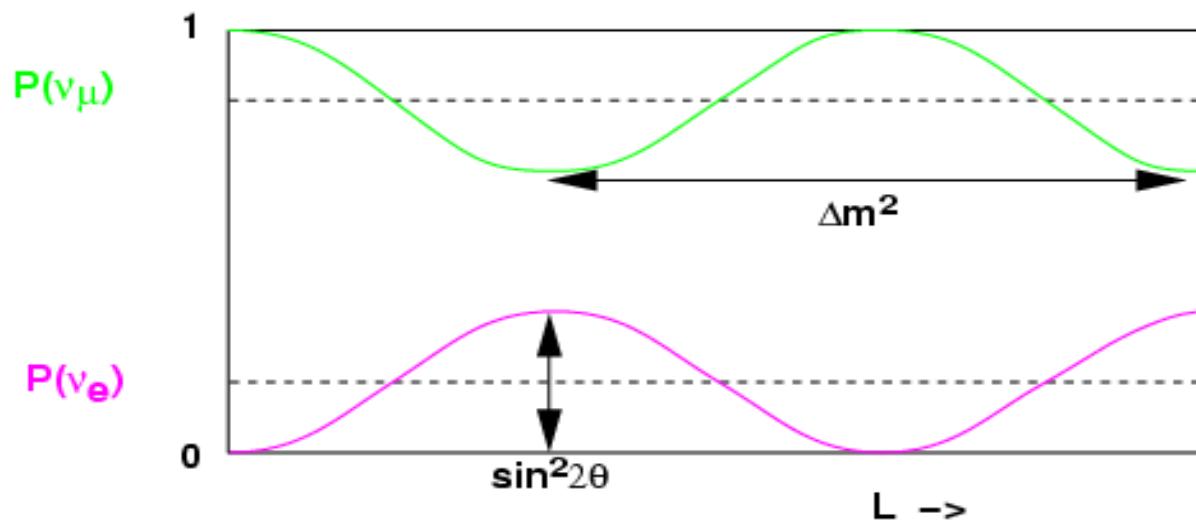
Weak Eigenstates

$$\nu_\mu \\ \nu_e$$

=  
=

Eigenstates of Propagation

$$\cos\theta \nu_1 + \sin\theta \nu_2 \\ -\sin\theta \nu_1 + \cos\theta \nu_2$$



$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L/E_\nu)$$

$$\Delta m^2 = m_2^2 - m_1^2 \text{ in eV}^2, \text{ L in meters, } E_\nu \text{ in MeV}$$

For oscillations to occur, neutrinos must have mass! <sup>3</sup>

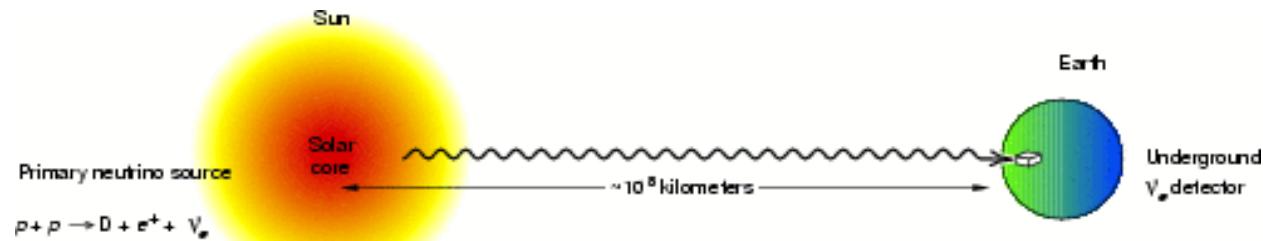
# Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_i \sum_j |U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}| \sin^2(1.27 \Delta m_{ij}^2 L / E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

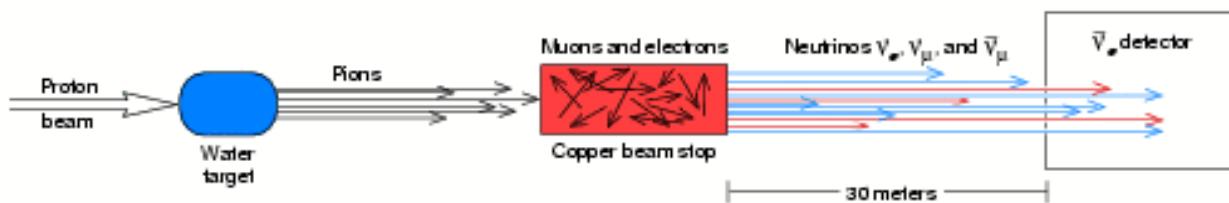
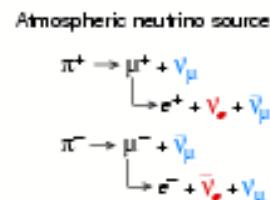
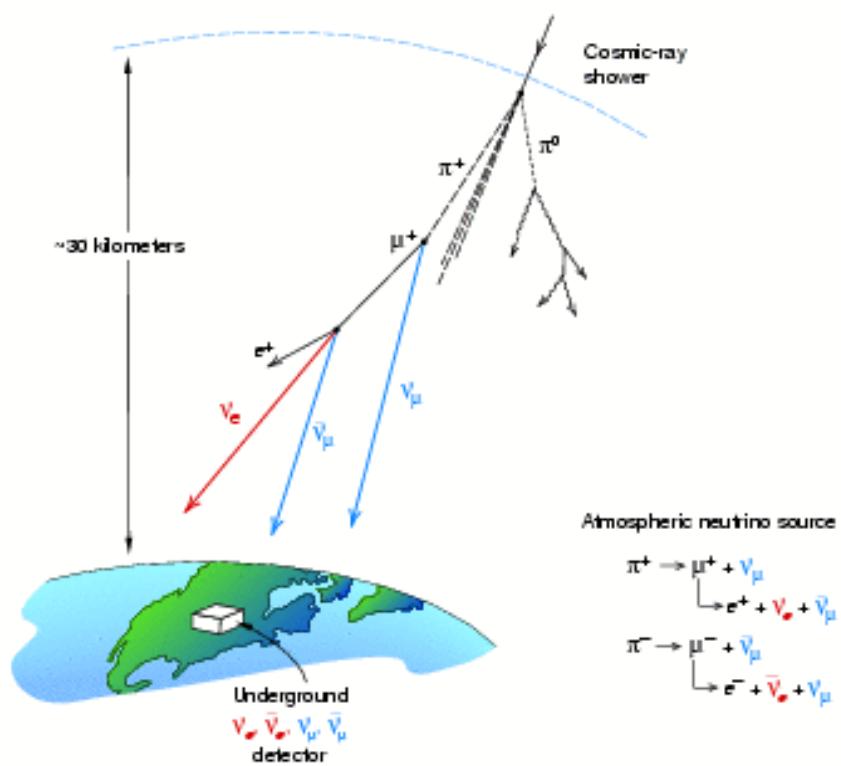
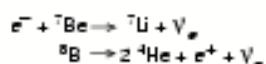
N	# $\Delta m_{ij}^2$	# $\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

# Neutrino Oscillations Have Been Observed!



**SuperK, SNO, Kamland  
(Very long baseline)**

Other sources of neutrinos:



**SuperK, K2K, MINOS  
(intermediate baseline)**

**LSND?  
(short baseline)**

# What are Short Baseline Oscillations?

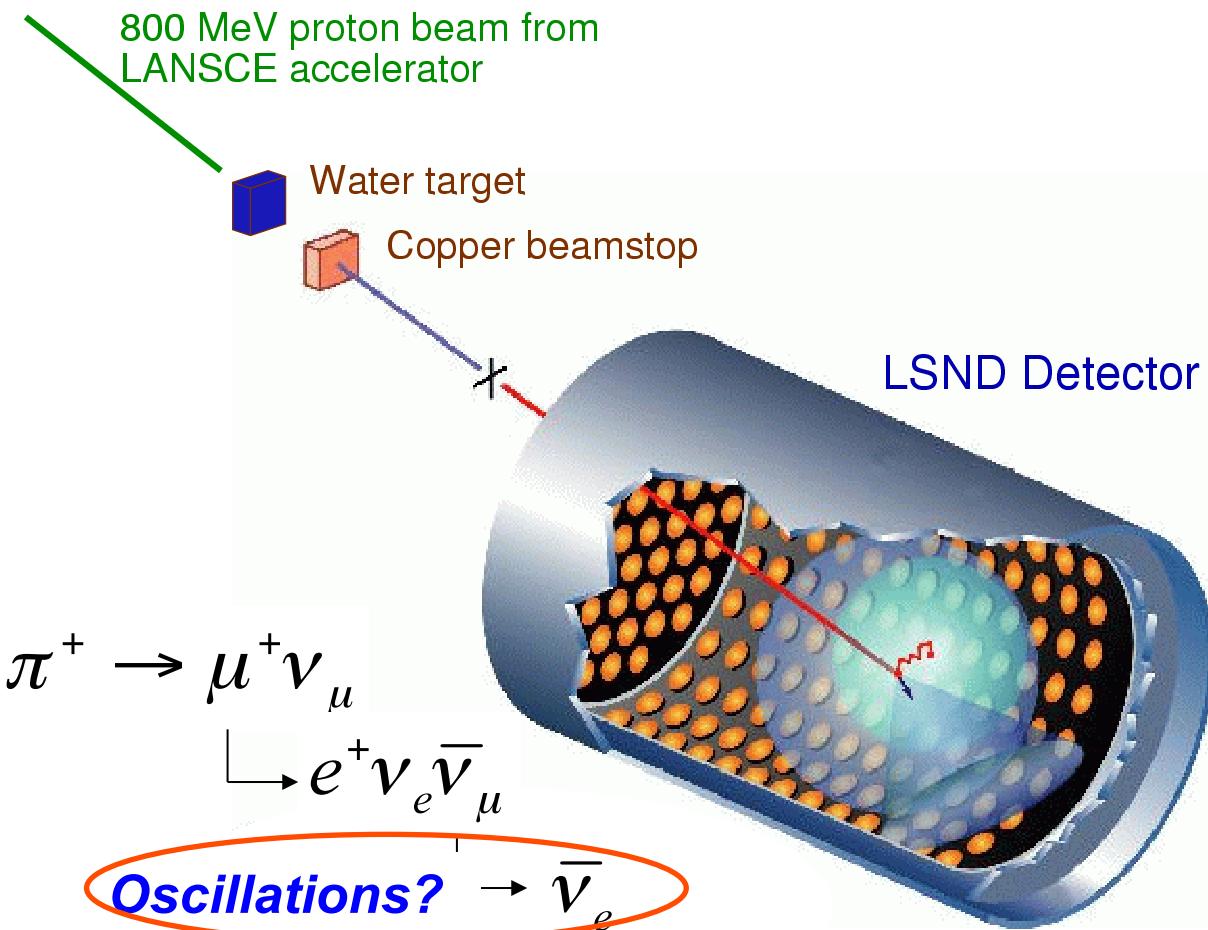
- They are typically defined as  $L$  less than a few kilometers.
- However, the important oscillation variable is  $L/E$ , where typically it is  $\sim 1$  in short baseline oscillations. This corresponds to a  $\Delta m^2 \sim 1\text{eV}^2$ .
  - Note that  $L/E$  is proportional to the  $\nu$  lifetime in its CM frame (proper time).
- It turns out there are many different types of experiments sensitive to this physics.
  - Accelerators: LSND, Karmen, MiniBooNE, Minos
  - Reactors:  $L/E \sim 5\text{m}/5\text{MeV}$
  - Radioactive source experiments:  $L/E \sim 1\text{m}/1\text{MeV}$
  - IceCube (atmospheric  $\nu$ ):  $L/E \sim 1000\text{km}/1\text{TeV}$

# What physics can be probed with short baseline experiments?

- Neutrino-Nucleus scattering
- Light sterile neutrinos
- Neutrino Decay
- CP violation:  $\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$
- CPT violation:  $\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha$
- Lorentz Violation (sidereal time)
- Dark Matter
- Non Standard Interactions
- Extra Dimensions

# LSND and the latest MiniBooNE Results

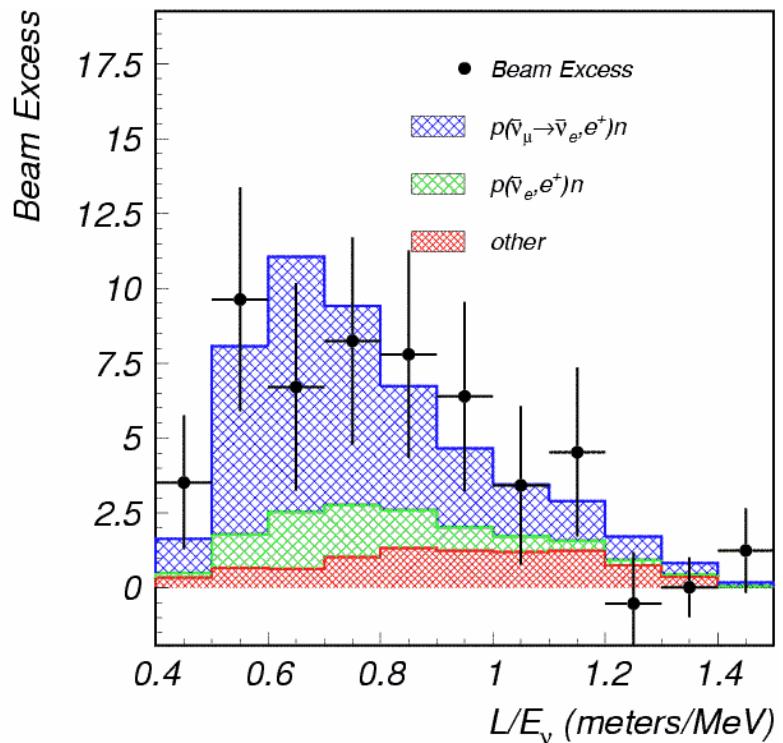
## The LSND Experiment: Evidence for Oscillations



Signal:  $\bar{\nu}_e p \rightarrow e^+ n$

$\downarrow n p \rightarrow d \gamma(2.2\text{MeV})$

HARP recently announced measurements that confirm LSND  $\bar{\nu}_e$  background estimate



LSND took data from 1993-98  
 - 49,000 Coulombs of protons  
 -  $L = 30\text{m}$  and  $20 < E_\nu < 53\text{ MeV}$

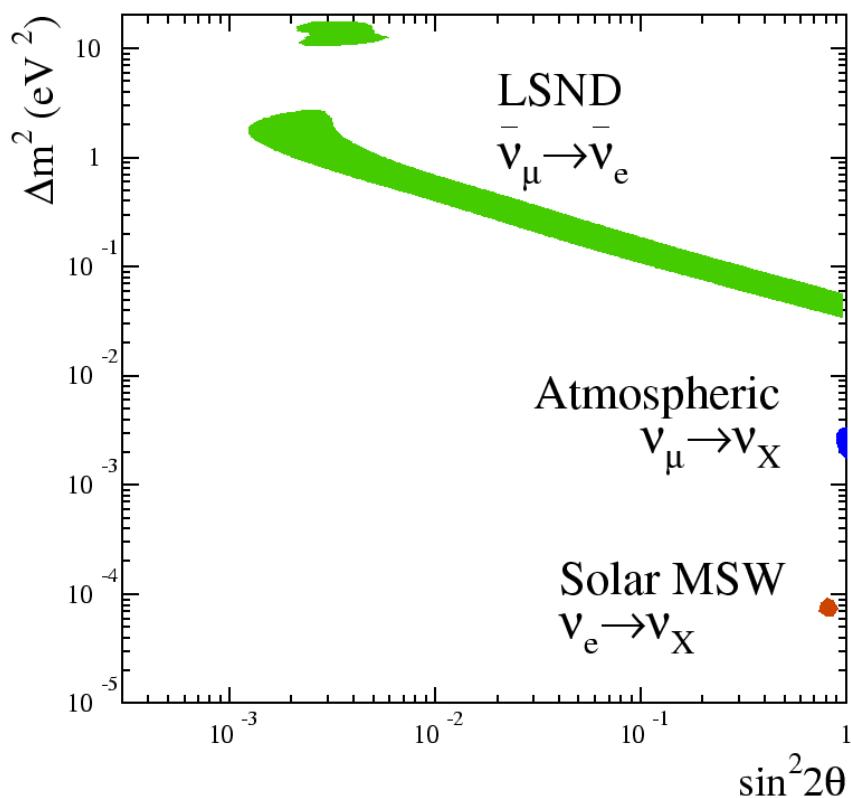
Saw an excess of  $\bar{\nu}_e$  :  
 $87.9 \pm 22.4 \pm 6.0$  events.

With an oscillation probability of  
 $(0.264 \pm 0.067 \pm 0.045)\%$ .

**3.8  $\sigma$  evidence for oscillation.**

# The LSND Signal is at Odds with Standard Oscillations

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$



A three neutrino picture requires

$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

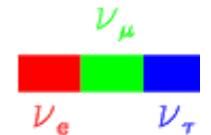
increasing (mass) $^2$



$$\Delta m_{23}^2 = m_2^2 - m_3^2$$



$$\Delta m_{12}^2 = m_1^2 - m_2^2$$

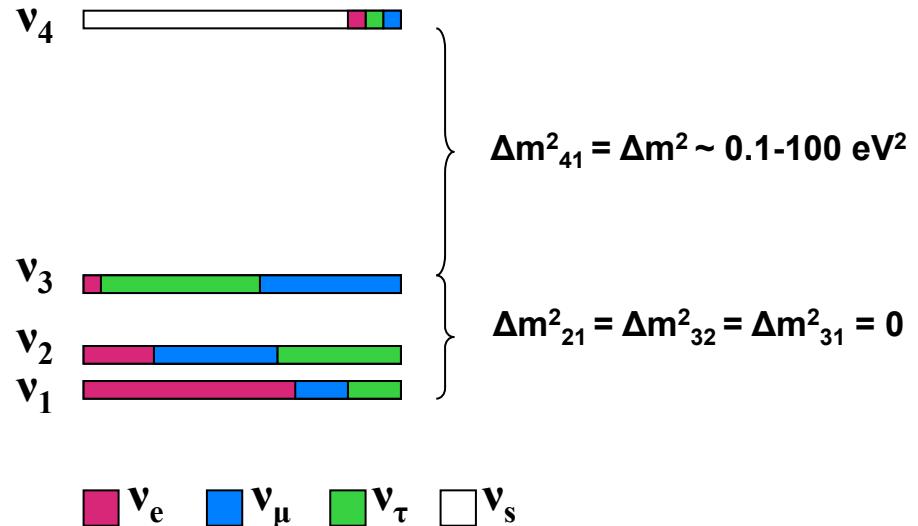


The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics

# LSND interpretation: simple two neutrino oscillations (3+1)

- Sterile neutrino models
  - 3+1

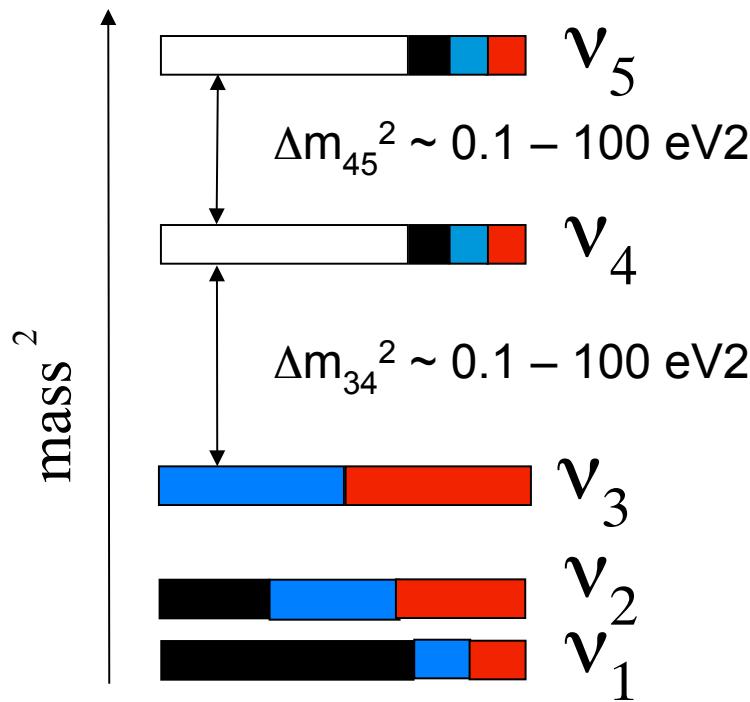
2-v approximation:



Oscillation probability:

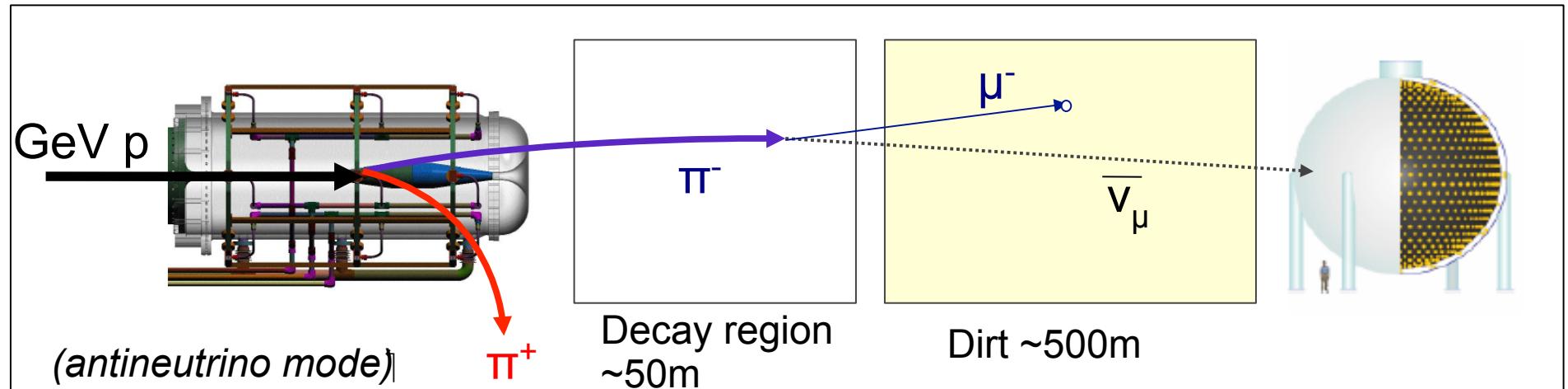
$$\begin{aligned} P(v_\mu \rightarrow v_e) &= 4|U_{\mu 4}|^2 |U_{e 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \\ &= \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E) \end{aligned}$$

# 3+2 Sterile Neutrinos



- 3+N models
- For N=2, model allows CP violation for short baseline
  - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

# Follow up to LSND: The MiniBooNE Experiment



- Similar L/E as LSND
  - MiniBooNE  $\sim 500\text{m}/\sim 500\text{MeV}$
  - LSND  $\sim 30\text{m}/\sim 30\text{MeV}$
- Horn focused neutrino beam ( $p+Be$ )
  - Horn polarity  $\rightarrow$  neutrino or anti-neutrino mode
- 800 tons mineral oil Cherenkov detector
- Stable beam and detector running since early 2003
  - $6.46\text{e}20$  POT in neutrino mode
  - $8.58\text{E}20$  POT in antineutrino mode

# $\nu_e$ Event Rate Predictions

$$\# \text{Events} = \text{Flux} \times \text{Cross-sections} \times \text{Detector response}$$

External measurements  
(HARP and E916)  
 $\nu_\mu$  rate constrained by neutrino data

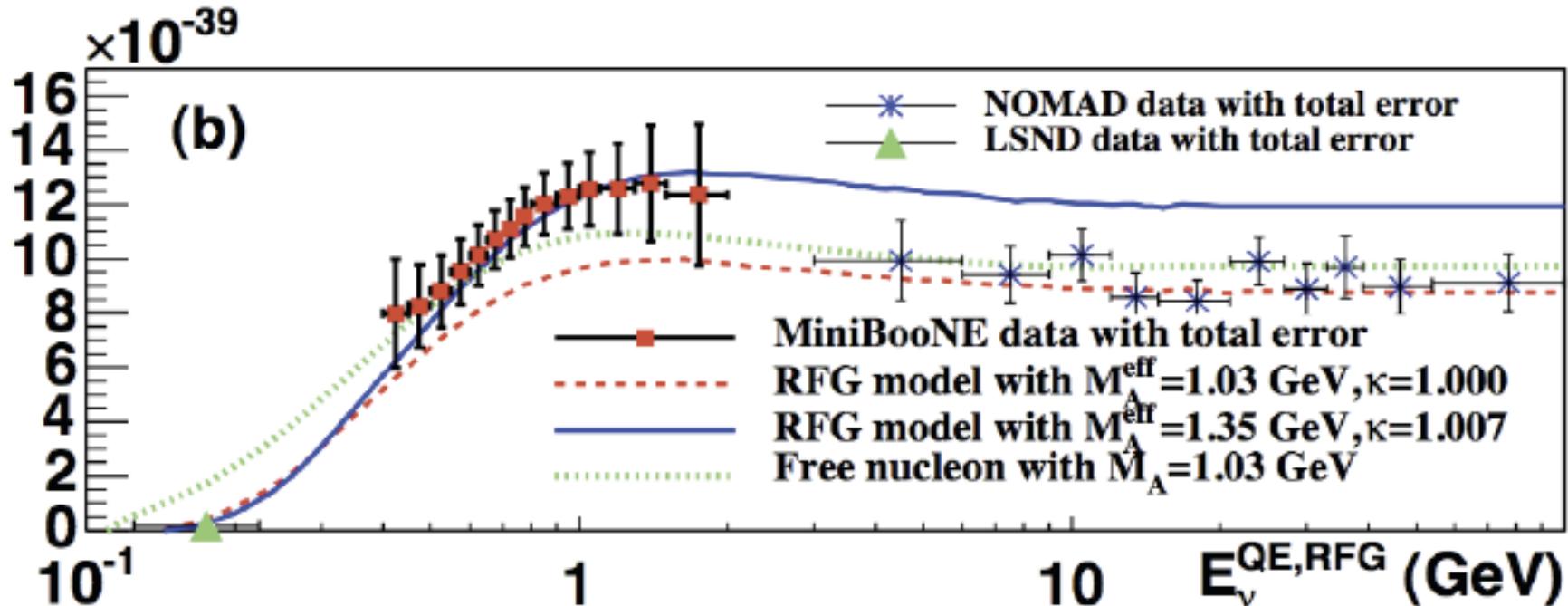
External and MiniBooNE Measurements  
 $\pi^0, \Delta \rightarrow N\gamma$ , dirt, and intrinsic  
 $\nu_e$  constrained from  $\nu_\mu$  data.

Detailed detector simulation and PID  
Checked with neutrino data and calibration sources.

- A. A. Aguilar-Arevalo et al., “Neutrino flux prediction at MiniBooNE”, Phys. Rev. D79, 072002 (2009).
  - A. A. Aguilar-Arevalo et al., “Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon”, Phys. Rev. Lett. 100, 032301 (2008).
  - A. Aguilar-Arevalo et al., “First Observation of Coherent  $\pi^0$  Production in Neutrino Nucleus Interactions with Neutrino Energy <2 GeV”, Phys. Lett. 664B, 41 (2008).
  - A. A. Aguilar-Arevalo et al., “Measurement of the Ratio of the  $\nu_u$  Charged-Current Single-Pion Production to Quasielastic Scattering with a 0.8 GeV Neutrino Beam on Mineral Oil”, Phys. Rev. Lett. 103, 081801 (2009).
  - A. A. Aguilar-Arevalo et al., “Measurement of  $\nu_u$  and  $\nu_d$  induced neutral current single  $\pi^0$  production cross sections on mineral oil at  $E_n \sim 1$  GeV”, Phys. Rev. D81, 013005 (2010).
  - A. A. Aguilar-Arevalo et al., “Measurement of the  $\nu_\mu$  charged current  $\pi^+$  to quasi-elastic cross section ratio on mineral oil in a 0.8 GeV neutrino beam”. Phys. Rev. Lett. 103:081801 (2010).
  - A. A. Aguilar-Arevalo et al., “First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section”, Phys. Rev. D81, 092005 (2010), arXiv: 1002.2680 [hep-ex].
  - A. A. Aguilar-Arevalo et al., “The MiniBooNE Detector”, Nucl. Instr. Meth. A599, 28 (2009).
  - P. Adamson et al., “Measurement of  $\nu_u$  and  $\nu_e$  Events in an Off-Axis Horn-Focused Neutrino Beam”, Phys. Rev. Lett. 102, 211801 (2009).
  - R.B. Patterson et al, “The Extended-Track Event Reconstruction for MiniBooNE”, Nucl. Instrum. Meth. A608, 206 (2009).
- Neutrino event rate ~5 times larger than the antineutrino rate at  $E \sim 1$  GeV.

# $\nu_\mu$ CCQE Scattering

A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).



Extremely surprising result - CCQE  $\sigma_{\nu\mu}(^{12}\text{C}) > 6 \sigma_{\nu\mu}(\text{n})$

How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

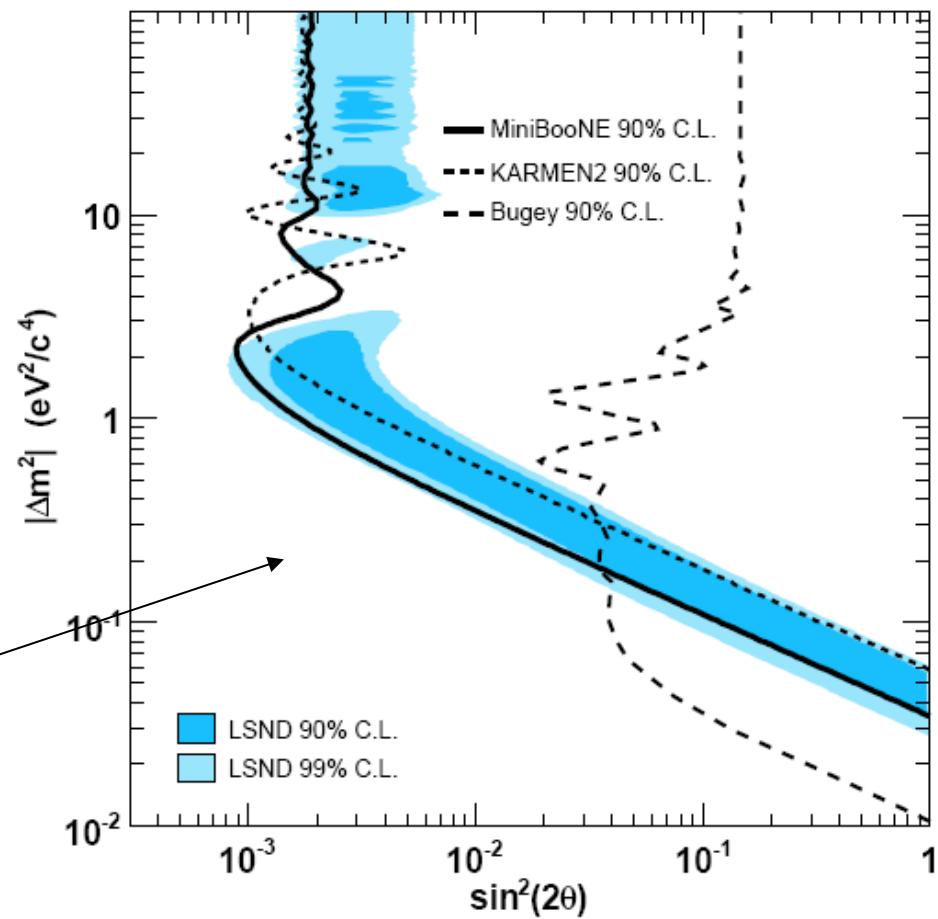
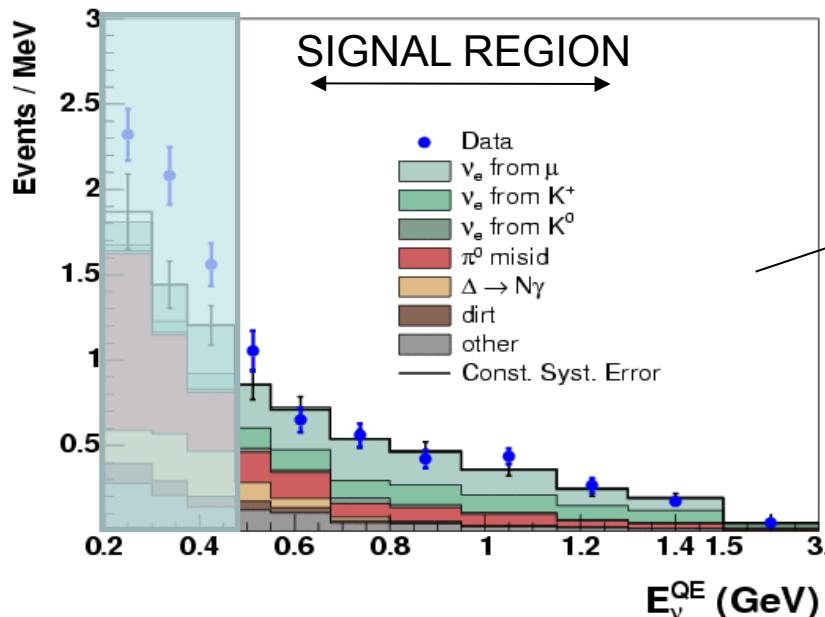
A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys. Rev. C65, 024002 (2002) & Gerry Garvey.

Effect could potentially change definition of reconstructed neutrino energy.

# MiniBooNE Neutrino Oscillation Results

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

- 6.46e20 POT
- No excess of events at higher energy ( $E>475$  MeV)
- Ruled out simple  $2\nu$  oscillations as LSND explanation (assuming no CP violation)



Phys. Rev. Lett. 98, 231801 (2007)

# MiniBooNE Neutrino Oscillation Results

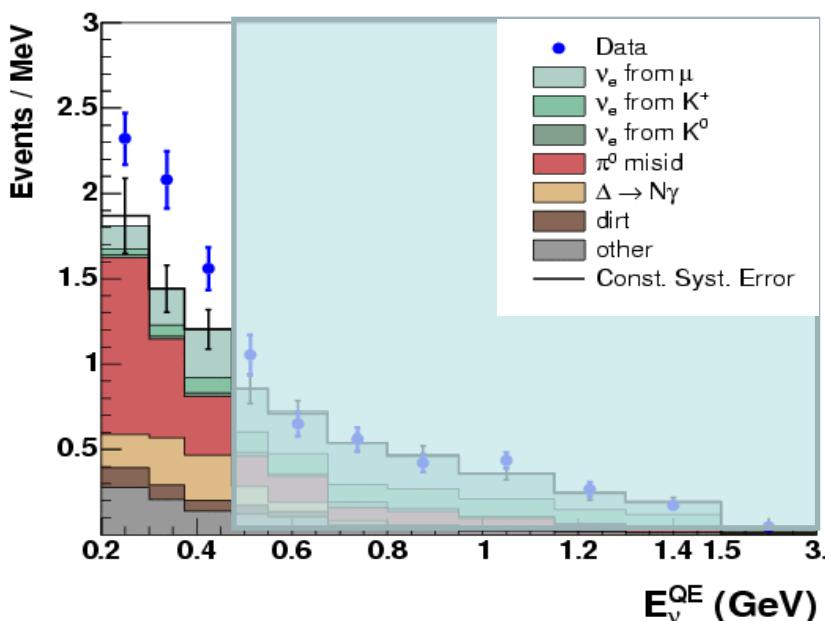
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess of events observed  
at lower energy:

$$128.8 \pm 20.4 \pm 38.3 \text{ (3.0}\sigma\text{)}$$

Shape not consistent with  
simple  $2\nu$  oscillations

Magnitude consistent with  
LSND



Anomaly Mediated Neutrino-Photon  
Interactions at Finite Baryon Density: Jeffrey  
A. Harvey, Christopher T. Hill, & Richard J. Hill,  
arXiv:0708.1281

CP-Violation 3+2 Model: Maltoni & Schwetz,  
arXiv:0705.0107; T. Goldman, G. J.  
Stephenson Jr., B. H. J. McKellar, Phys. Rev.  
D75 (2007) 091301.

Extra Dimensions 3+1 Model: Pas, Pakvasa, &  
Weiler, Phys. Rev. D72 (2005) 095017

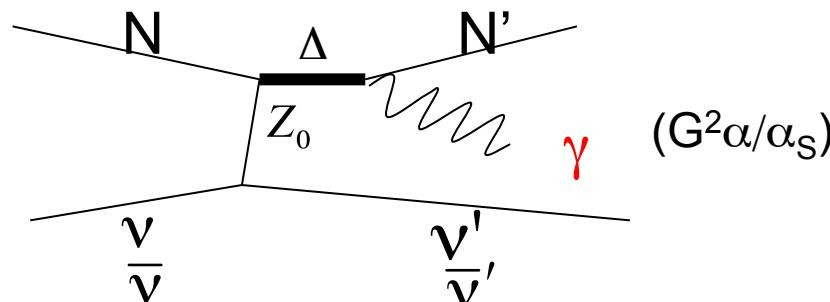
Lorentz Violation: Katori, Kostelecky, & Tayloe,  
Phys. Rev. D74 (2006) 105009

CPT Violation 3+1 Model: Barger, Marfatia, &  
Whisnant, Phys. Lett. B576 (2003) 303

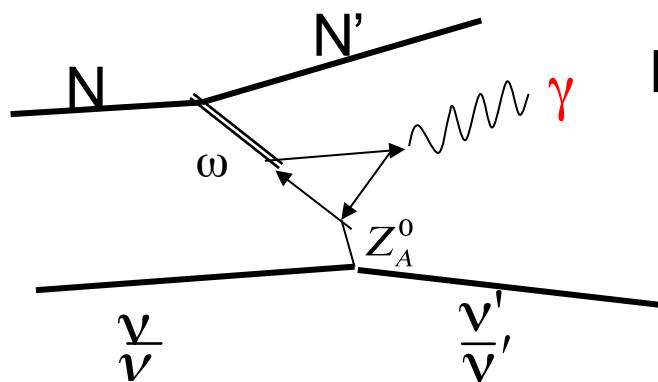
New Gauge Boson with Sterile Neutrinos: Ann  
E. Nelson & Jonathan Walsh, arXiv:0711.1363

# Sources of Gamma-Ray Backgrounds

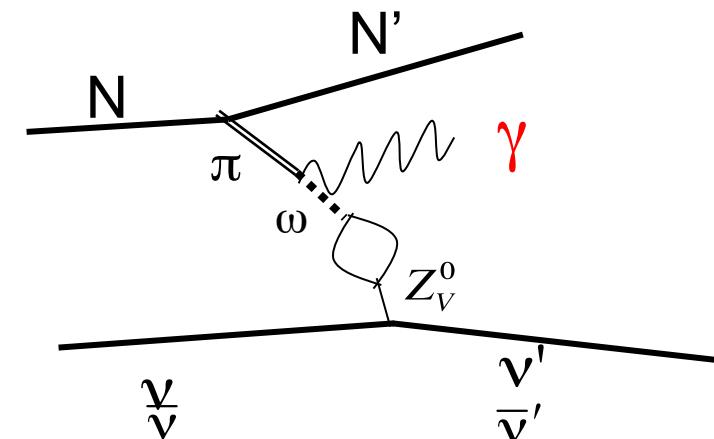
Dominant process  
accounted for in MC!



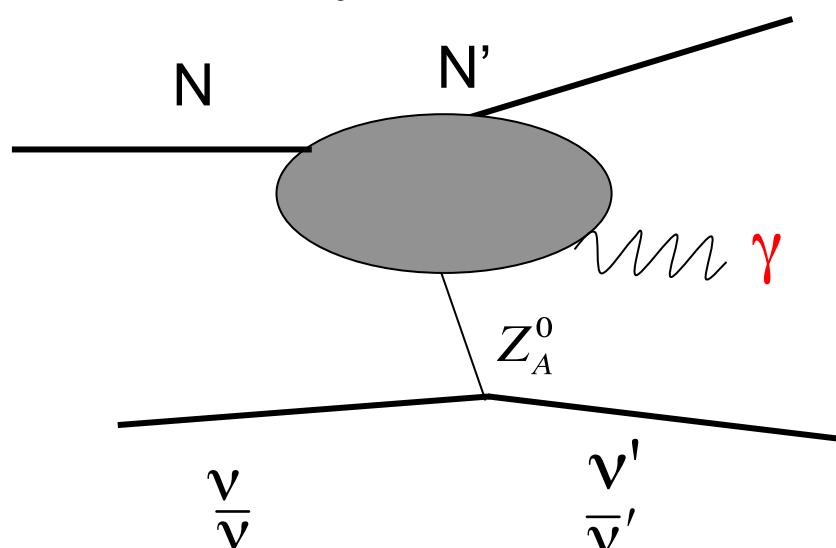
Radiative Delta Decay



Axial Anomaly



Other PCAC

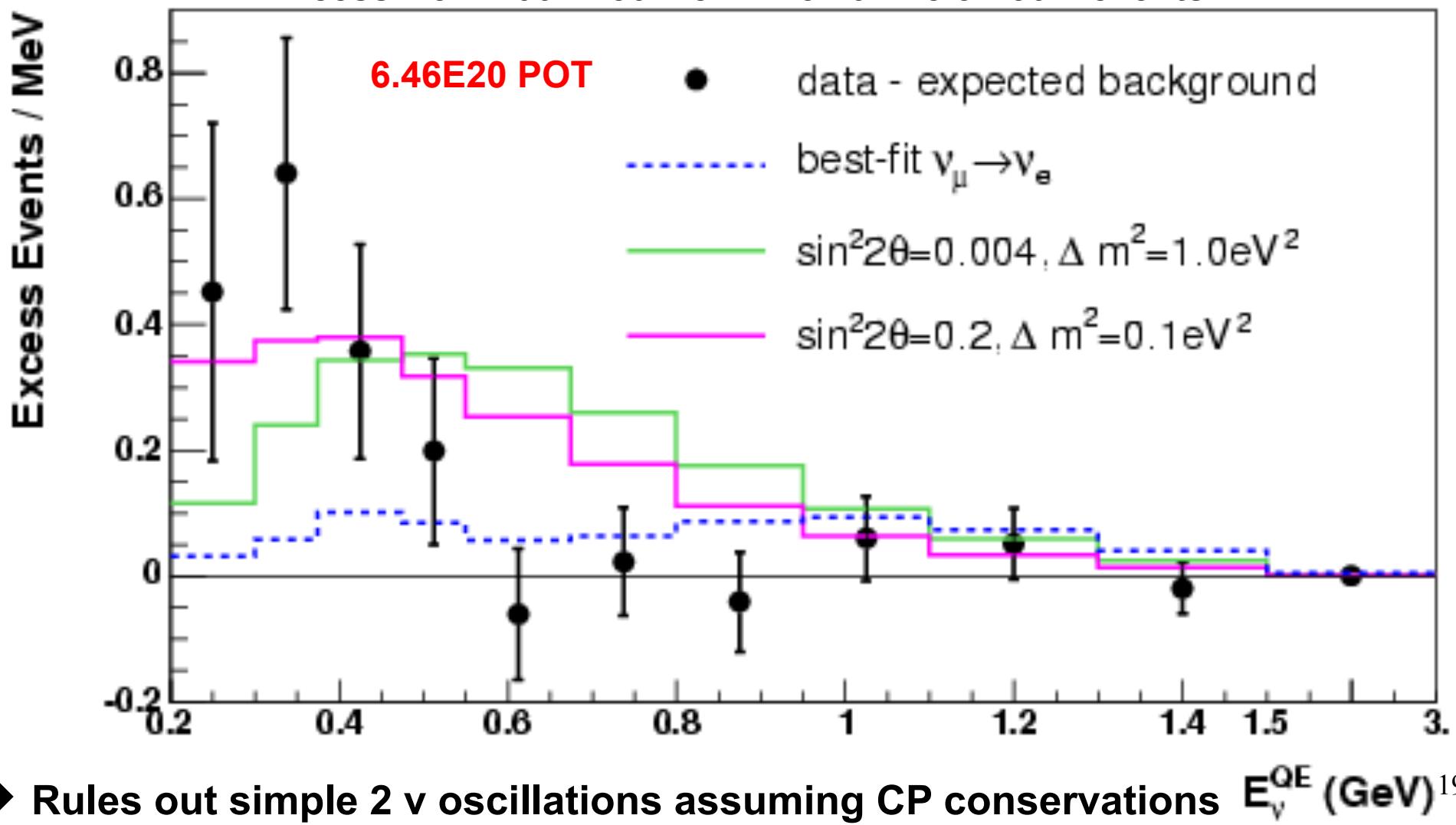


*So far no one has found a NC process to account for the  $\nu, \bar{\nu}$  difference & the  $\nu$  low-energy excess. Work is in progress:  
R. Hill, arXiv:0905.0291  
Jenkins & Goldman, arXiv:0906.0984  
Serot & Zhang, arXiv:1011.5913*

# MiniBooNE Data Show a Low-Energy Excess

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

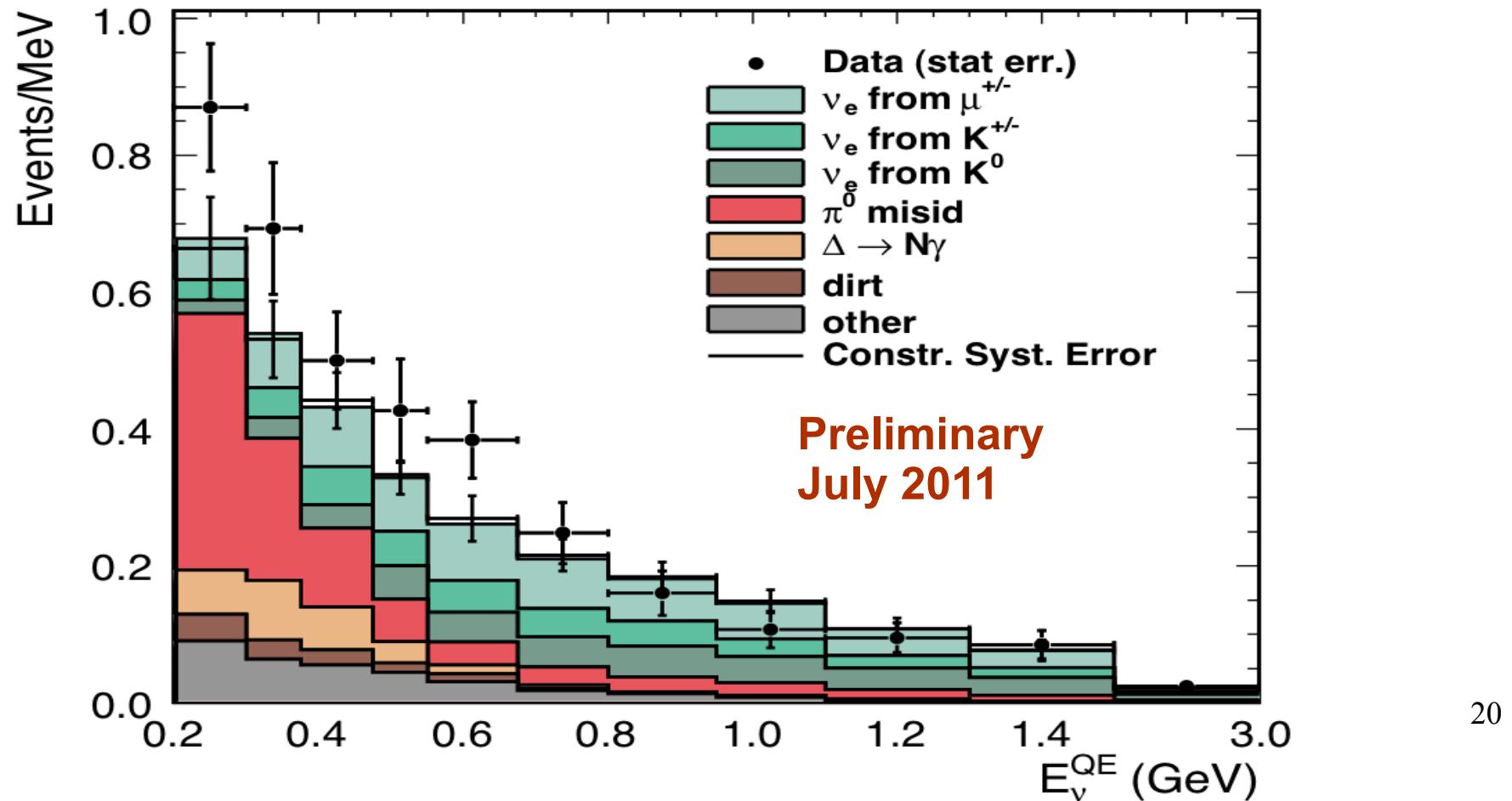
Excess from 200-475 MeV =  $128.8 \pm 20.4 \pm 38.3$  events  
Excess from 200-1250 MeV =  $151.0 \pm 28.3 \pm 50.7$  events



# MiniBooNE Antineutrino Oscillation Results

update of A. A. Aguilar-Arevalo, Phys. Rev. Lett. 105, 181801 (2010)

- 8.58E20 POT (~50% more data than published and new K<sup>+</sup> constraint from SciBooNE)
- Excess = 57.7+/-18.8+/-22.4 (200-3000 MeV)

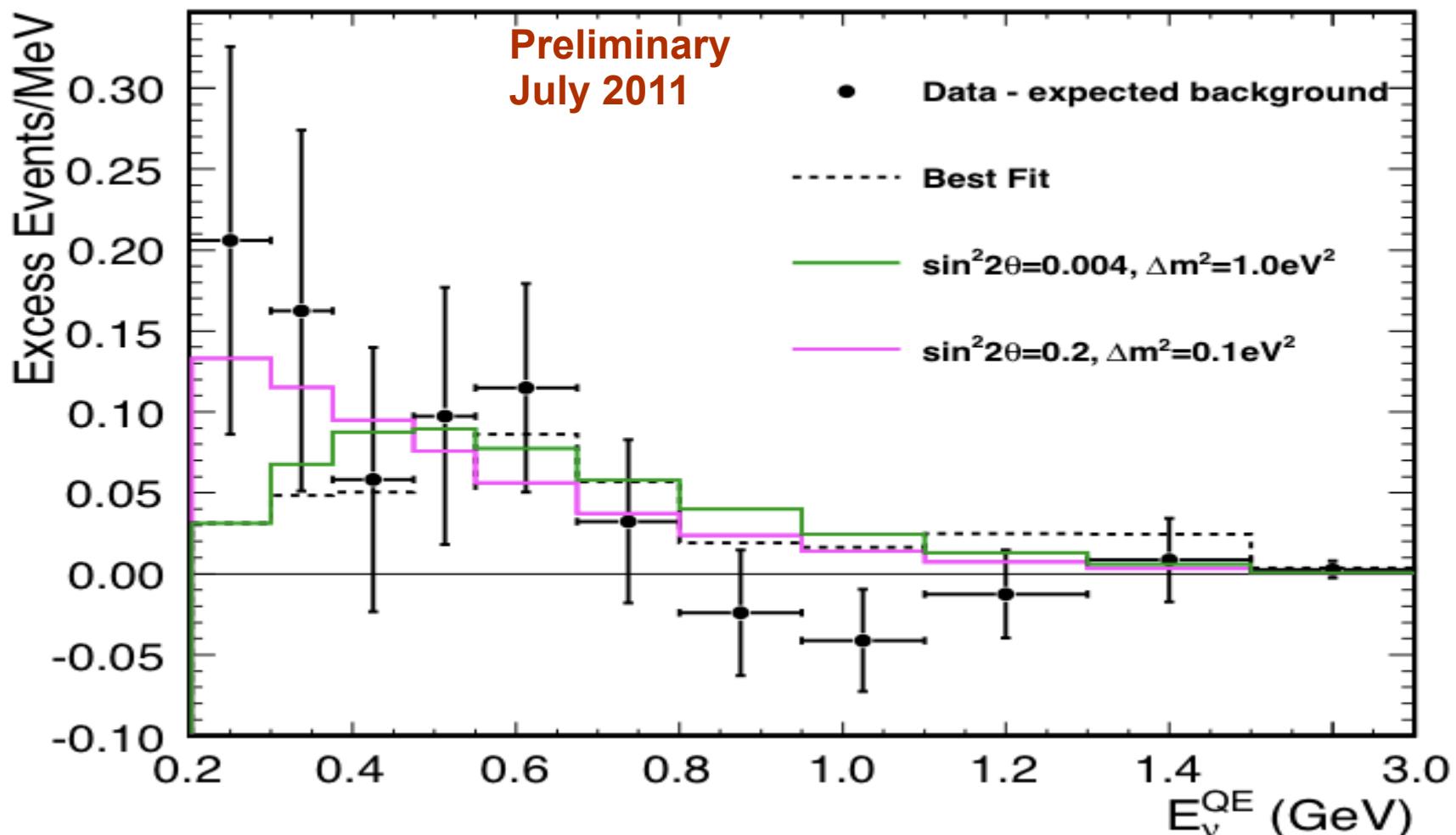


# MiniBooNE Antineutrino Oscillation Results

update of A. A. Aguilar-Arevalo, Phys. Rev. Lett. 105, 181801 (2010)

Excess =  $38.6 \pm 18.5$  (200-475 MeV)

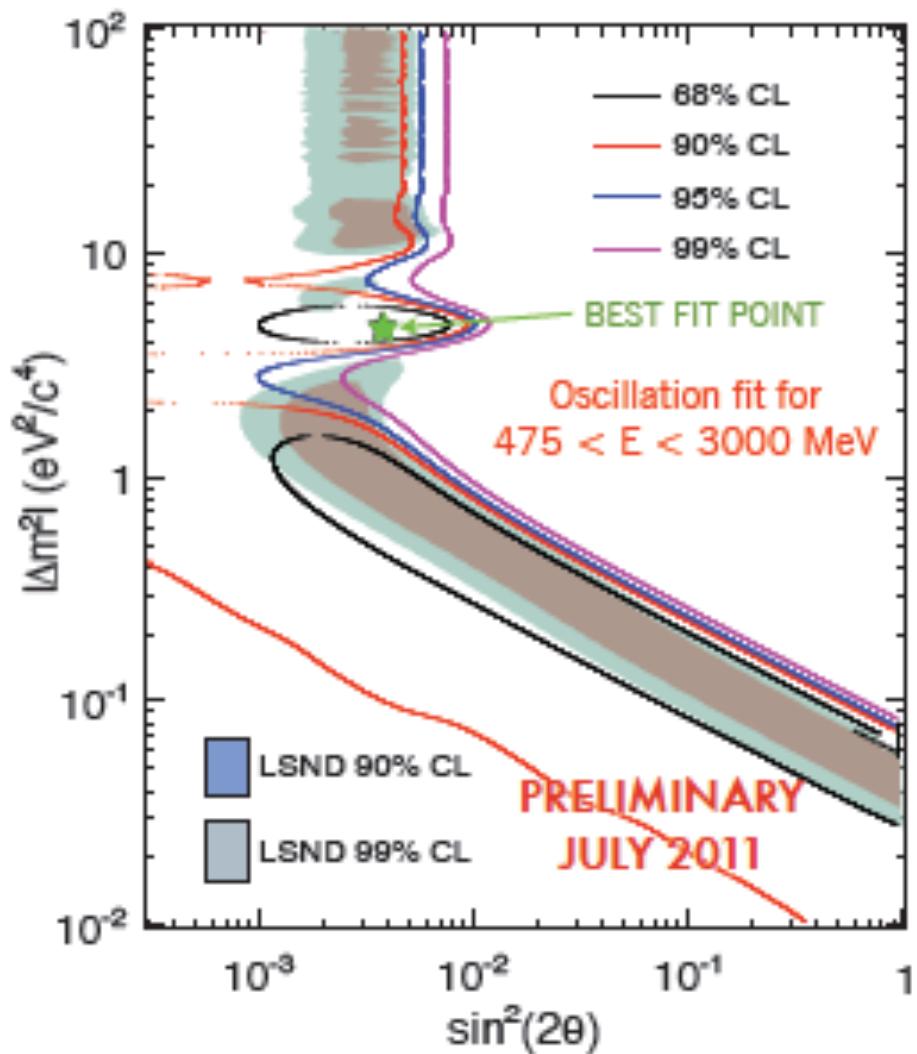
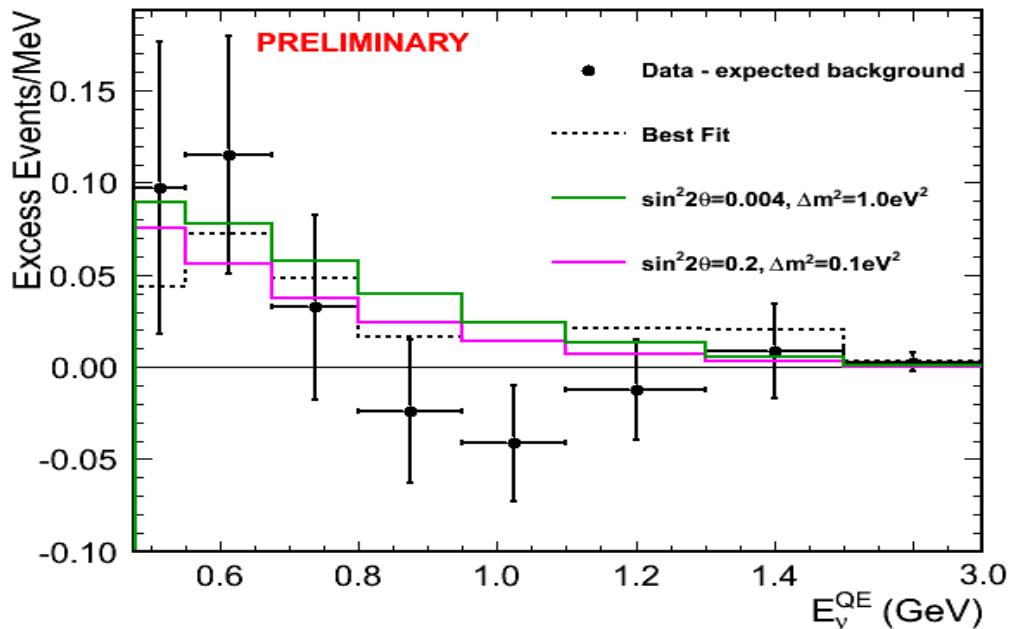
Excess =  $16.3 \pm 19.4$  (475-1250 MeV)



# MiniBooNE Oscillation Fit

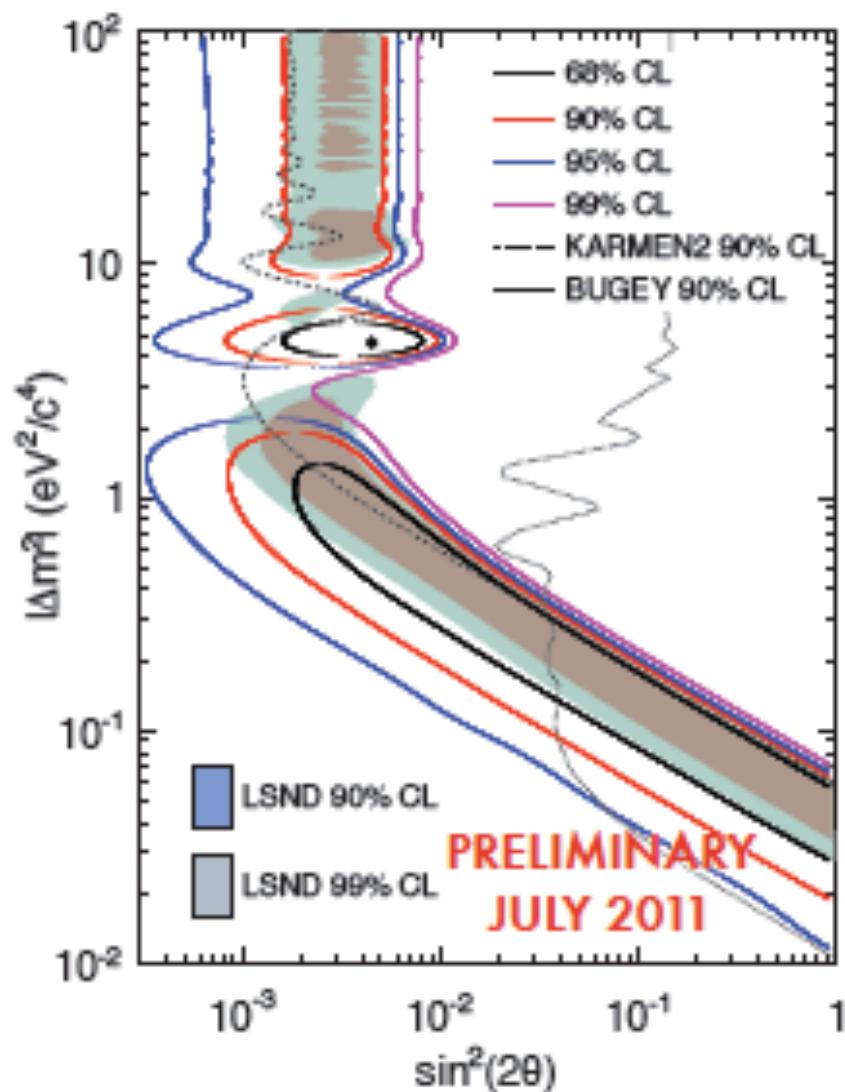
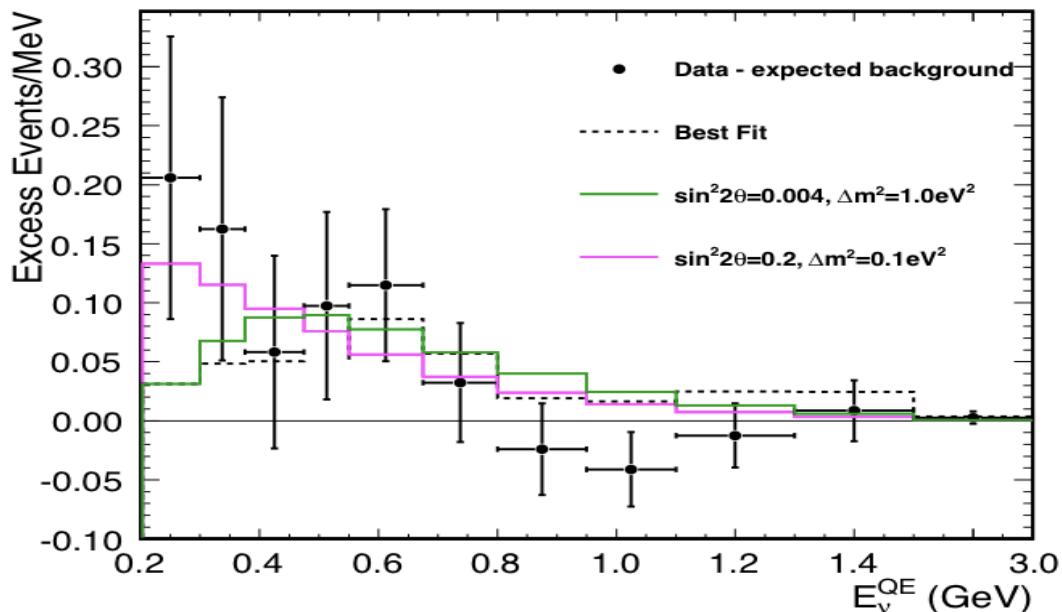
## $E > 475$

- 8.58E20 POT antineutrino mode
- $E > 475$  is official osc. region
- Oscillations favored over background only hypotheses at 91.4% CL (model dependent)
- $P(\text{null}) = 14.9\%$
- $P(\text{best fit}) = 35.5\%$



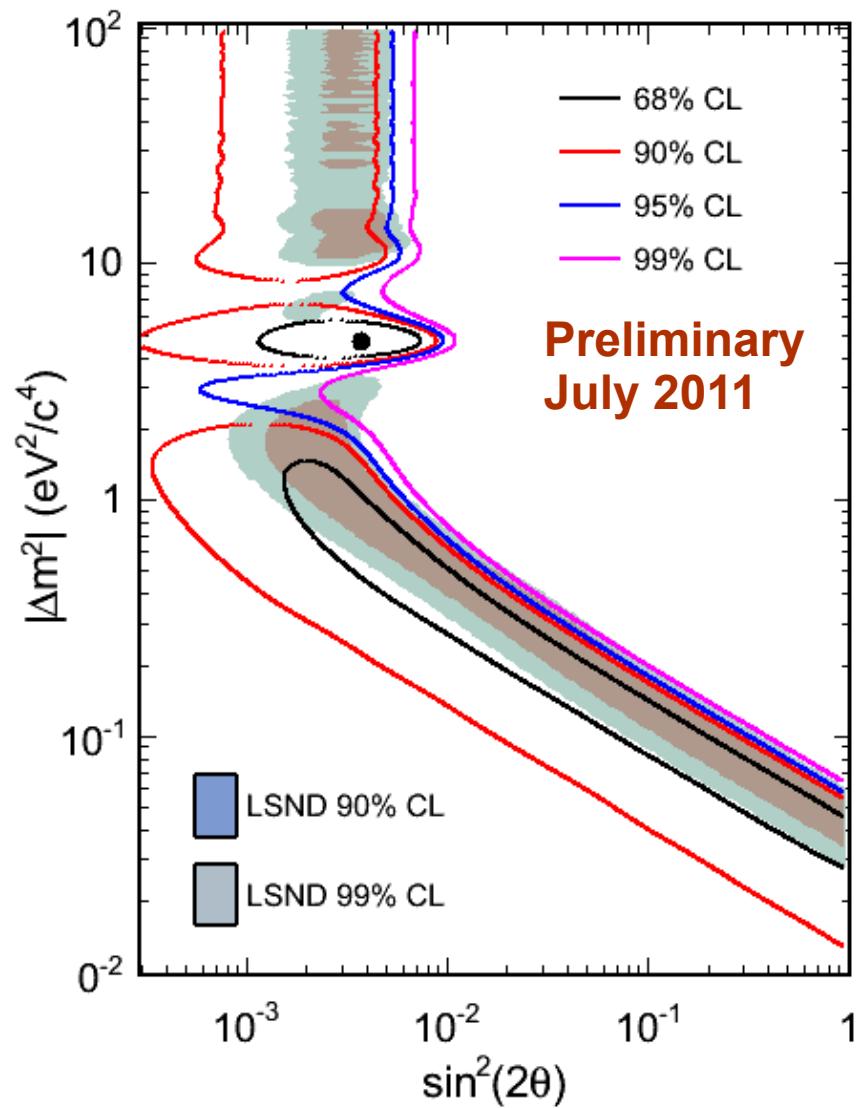
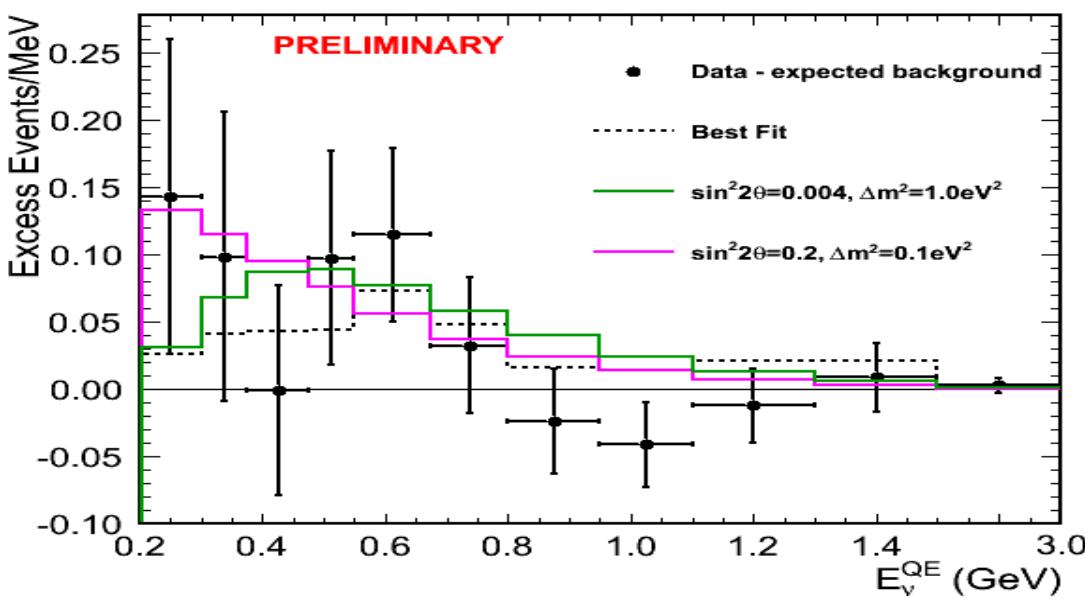
# E>200MeV

- 8.58E20 POT
- Oscillations favored over background only hypotheses at 97.6% CL (model dependent)
- No assumption made about low energy excess
- $P(\text{null}) = 10.1\%$
- $P(\text{best fit}) = 50.7\%$

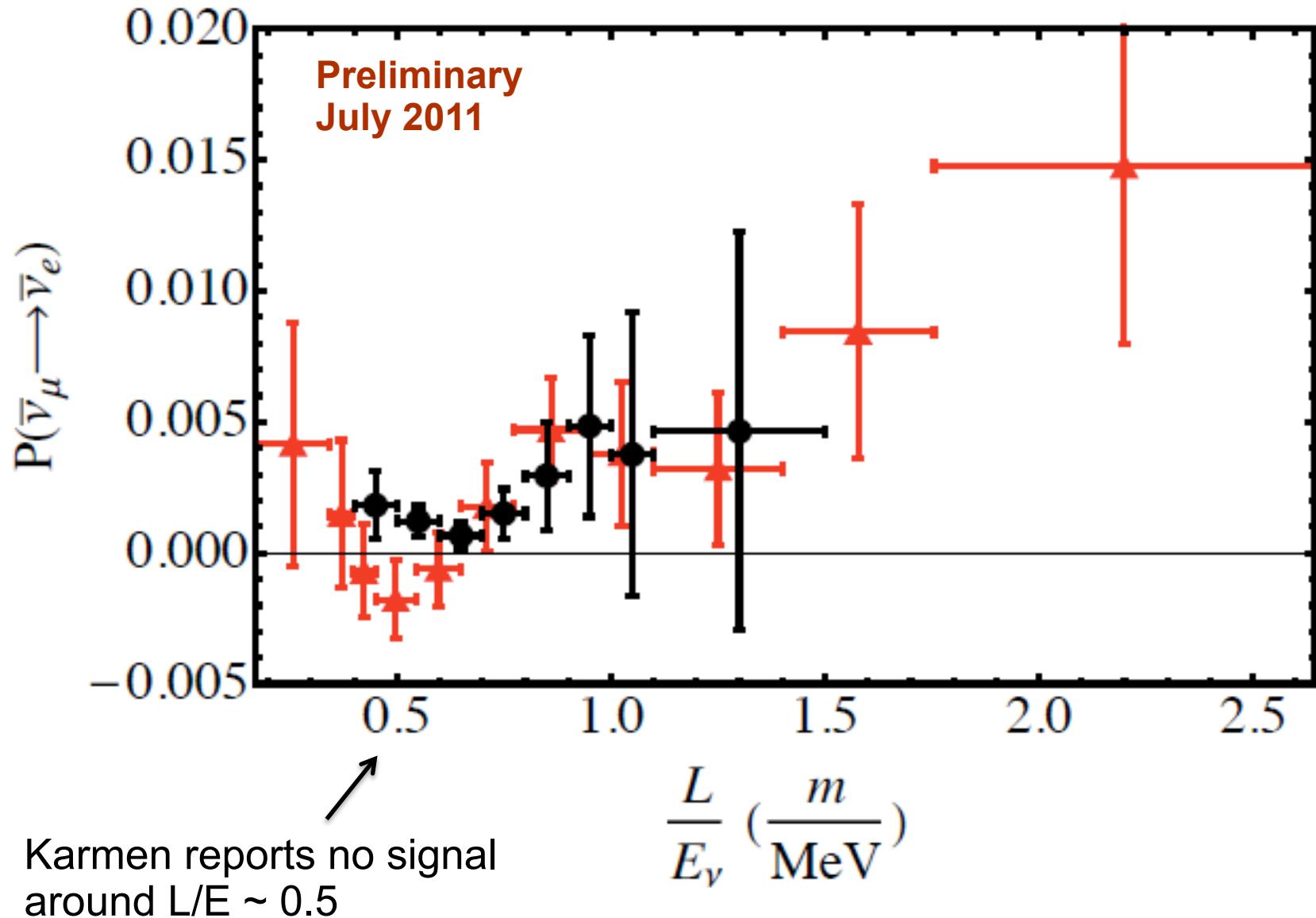


# E>200MeV

- 8.58E20 POT antineutrino mode
- Oscillations favored over background only hypotheses at 94.2% CL (model dependent)
- Subtract low energy excess assuming neutrinos in antinu mode contribute to excess (17 events)
- $P(\text{null}) = 28.3\%$
- $P(\text{best fit}) = 76.5\%$



# Model Independent Comparison of LSND & MiniBooNE Antineutrino mode



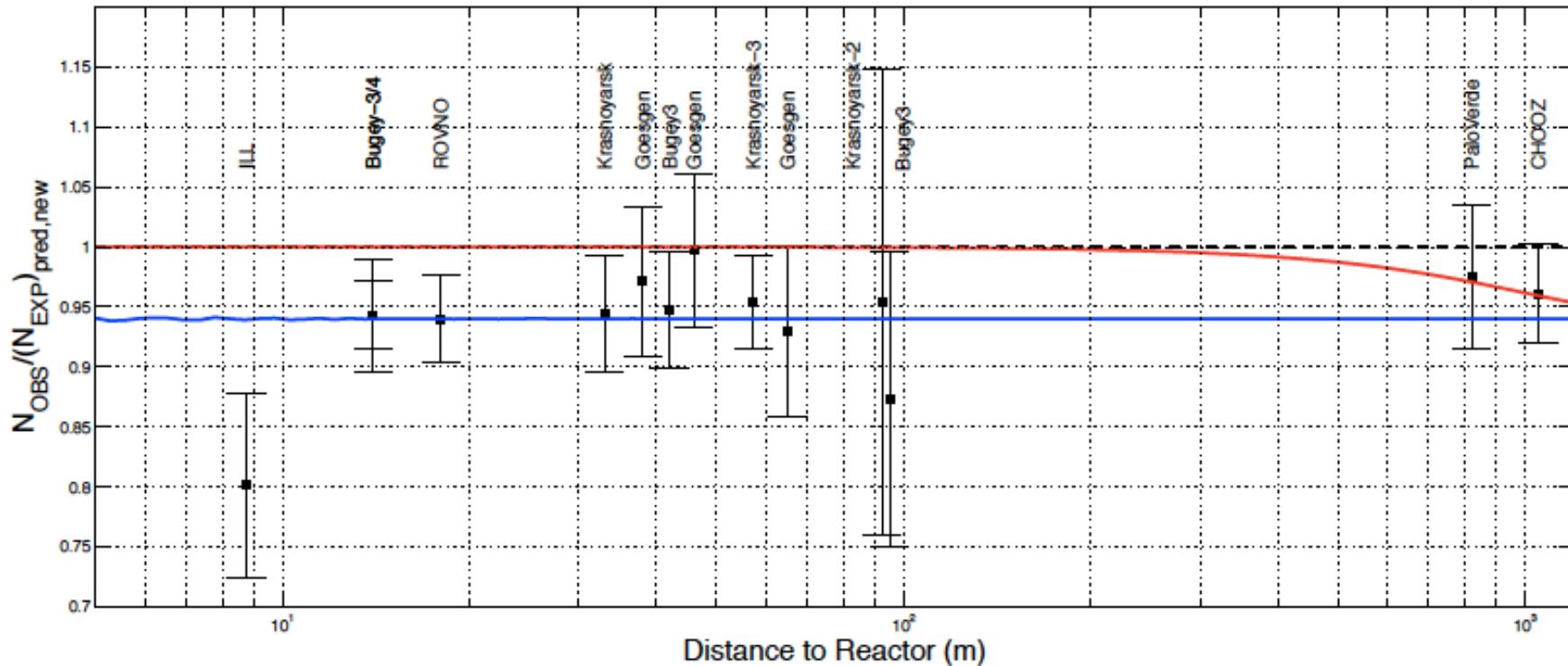
# Other L/E~1 Experiments and Interpretations

# Reactor Antineutrino Anomaly

## $\bar{\nu}_e$ Disappearance

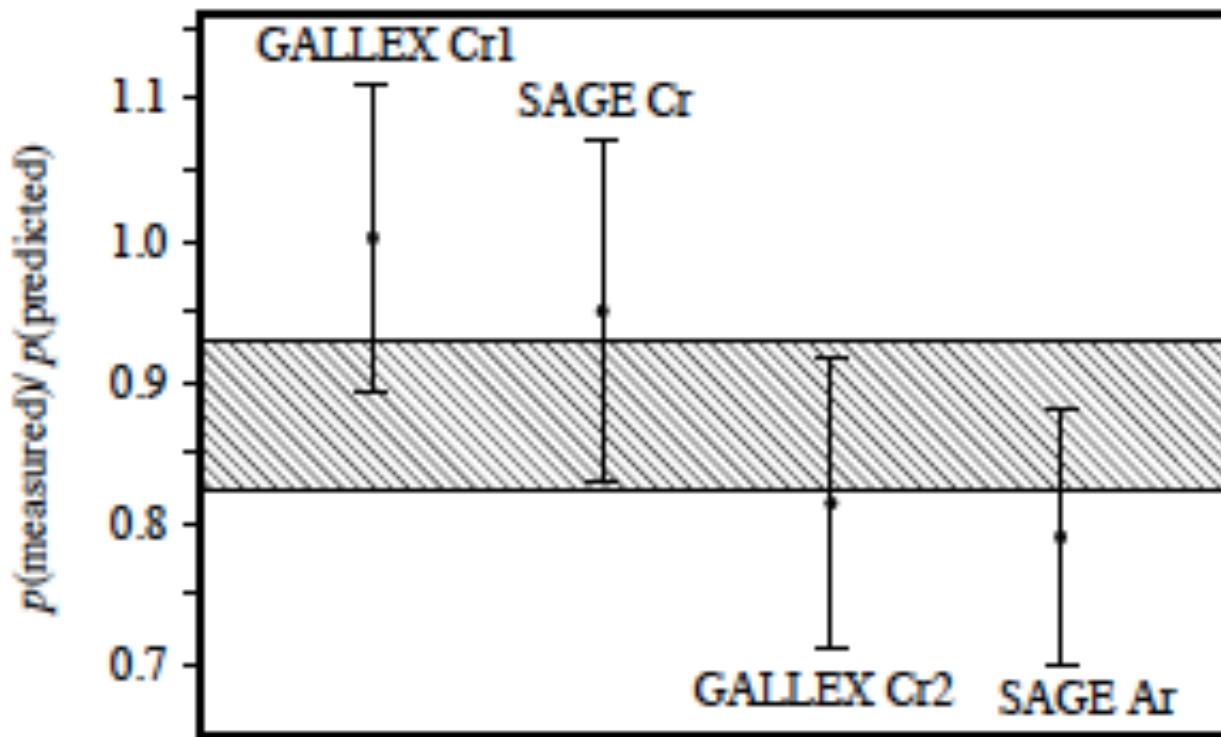
- Recent re-evaluation of reactor fluxes  $\rightarrow +3\%$ 
  - Reevaluation of cross sections and new neutron lifetime
- Observed/predicted event rate =  $0.943 \pm 0.023$
- Deviation from unity at 98.6% CL

*Phys.Rev.D 83, 073006 (2011)*



# Radioactive Neutrino Sources

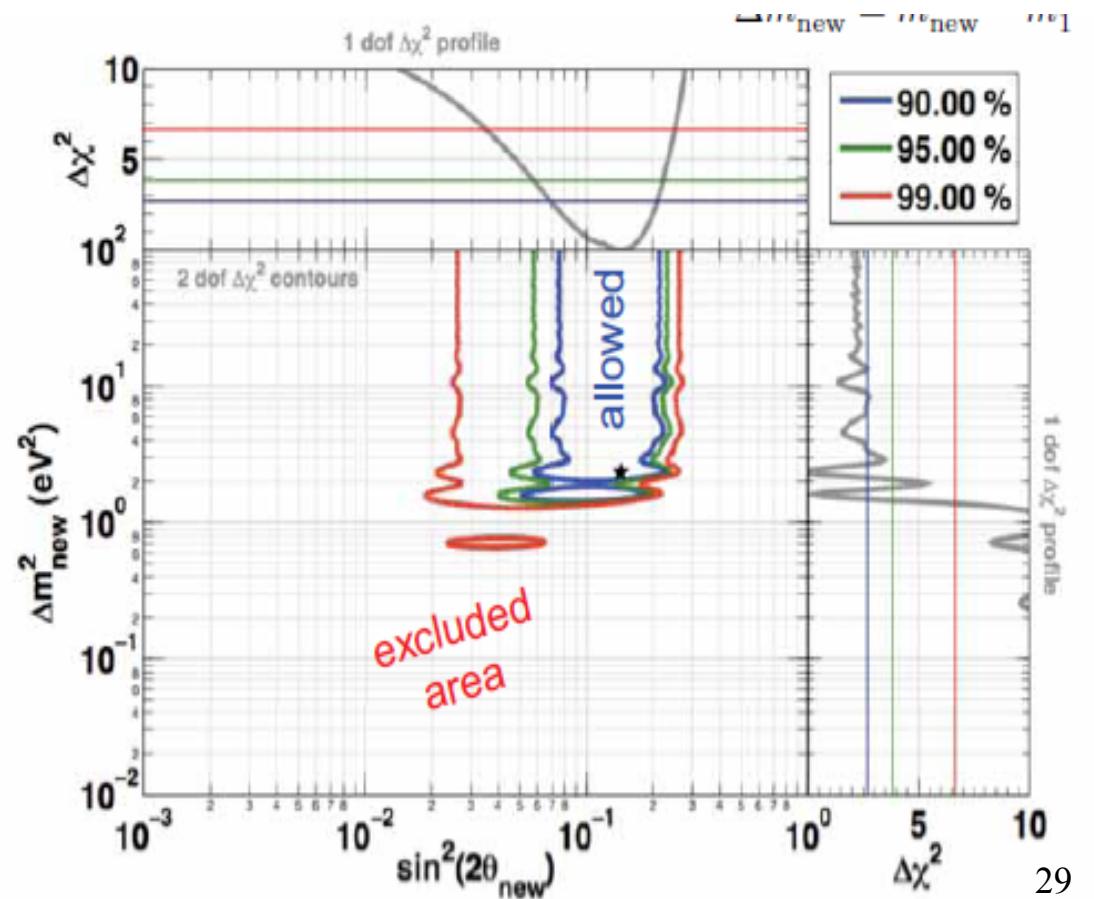
- Neutrinos detected through radiochemical counting of Ge nuclei:  ${}^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^-$
- GALLEX and SAGE calibration runs with intense MCi sources ( $\nu_e$ )



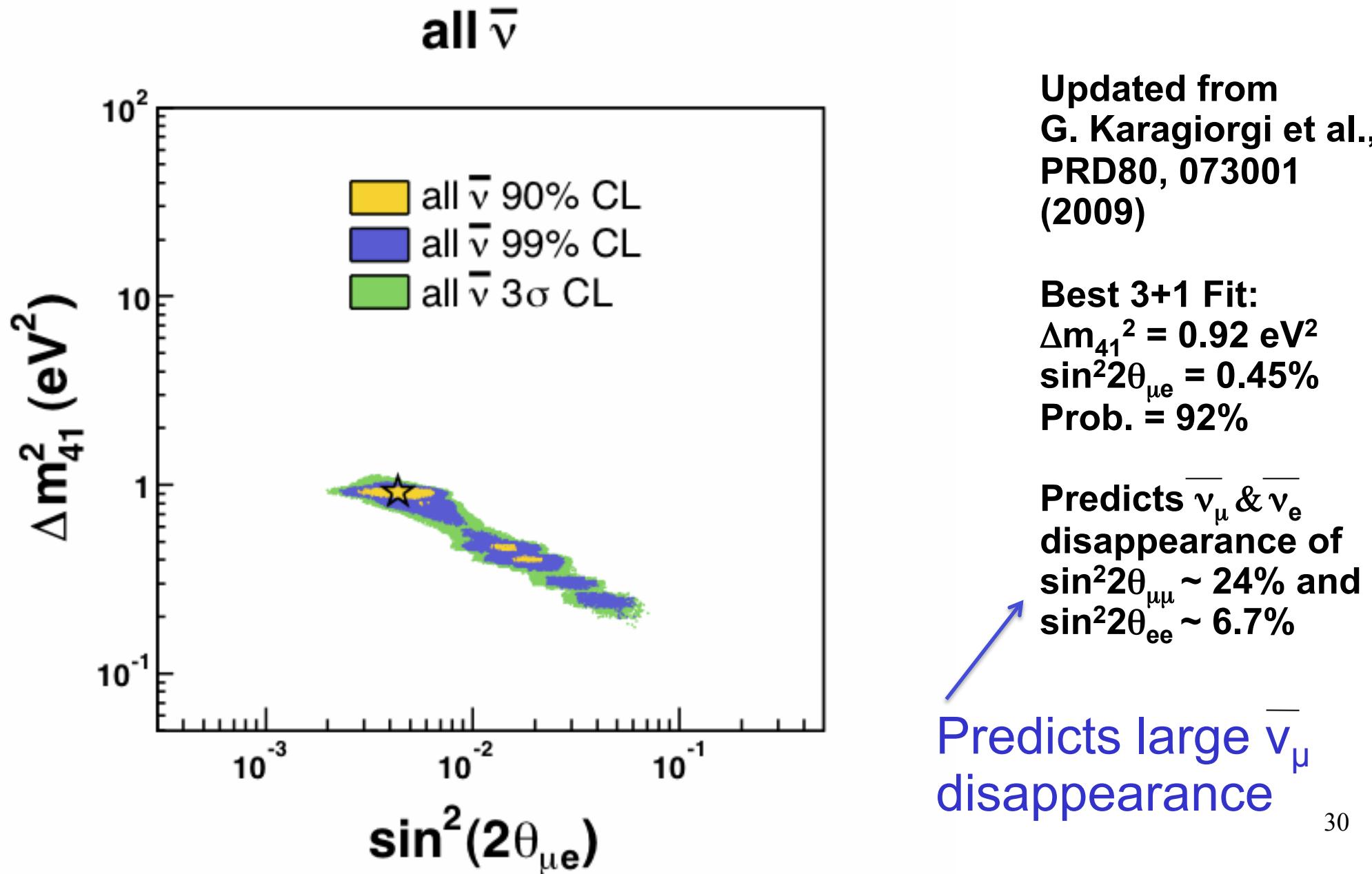
$R=0.86\pm0.05$  (observed/predicted rate)

# Sterile neutrinos?

- Reactor data and GALLEX/SAGE
- Data consistent with sterile neutrino oscillations at  $\Delta m^2 \sim 1.5 \text{ eV}^2$  and  $\sin^2(2\theta) \sim 0.14$ .
- Null disfavored at 99.8%



# 3+1 Global Fit to World Antineutrino Data (including new reactor $\bar{\nu}$ normalization)



# 3+N Models Requires Large $\bar{\nu}_\mu$ Disappearance!

For sterile neutrino oscillations:  $\bar{\nu}_\mu \rightarrow \bar{\nu}_s \rightarrow \bar{\nu}_e$

In general,  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

Reactor Experiments:  $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) \sim 10\%$

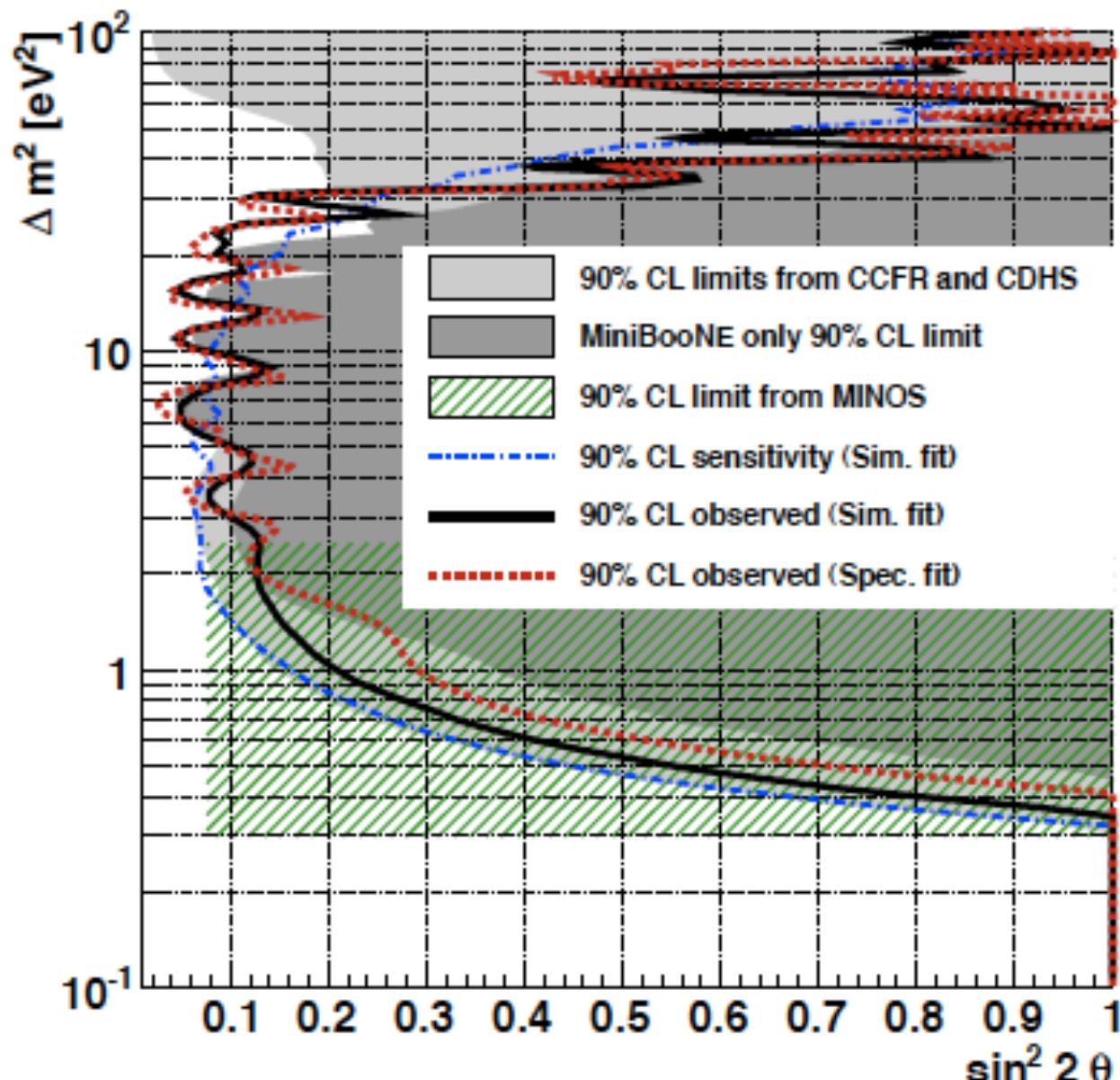
LSND/MiniBooNE:  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

Therefore:  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 10\%$

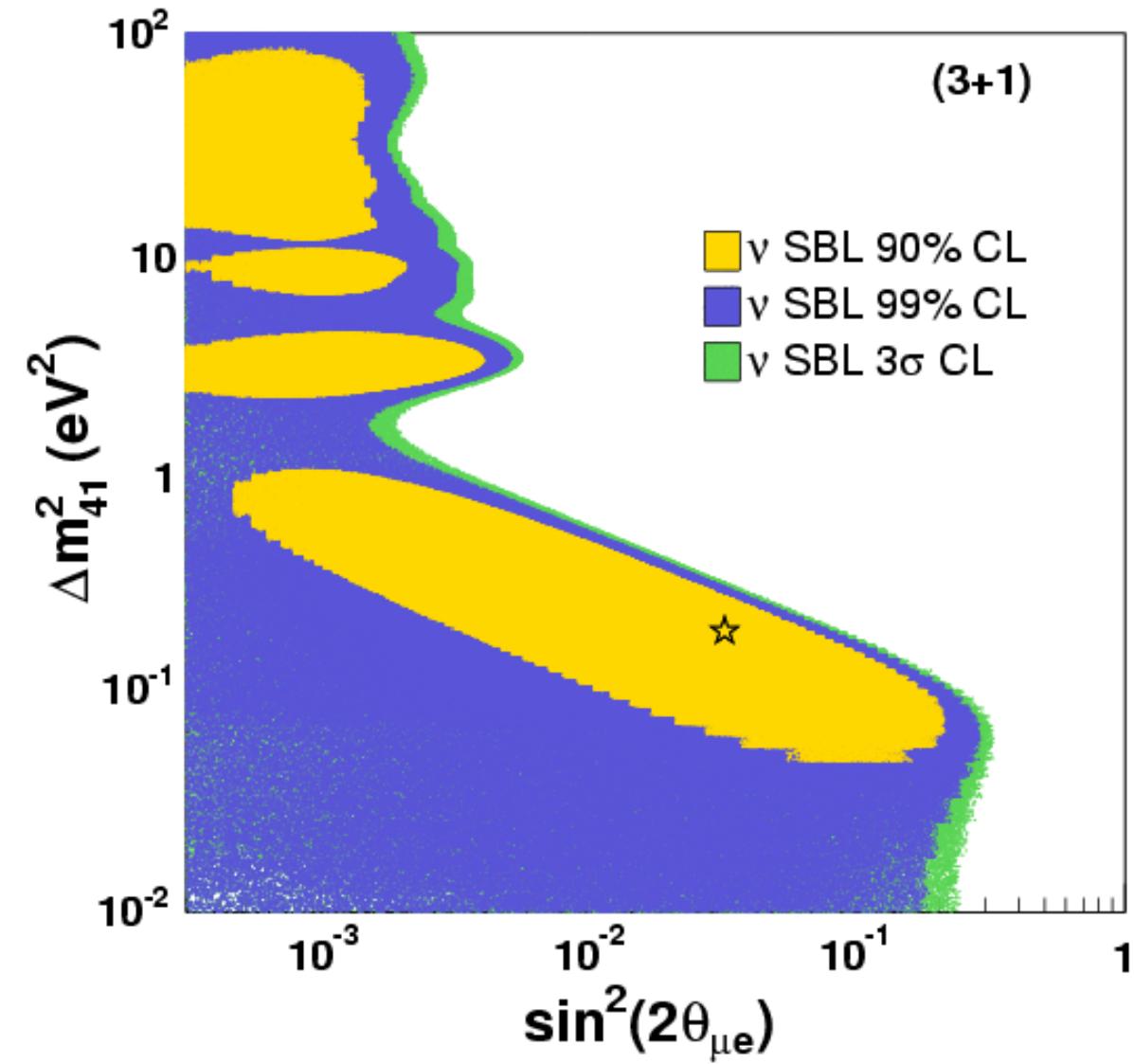
Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

# SciBooNE/MiniBooNE Neutrino Disappearance Limits (Antineutrino Next)

arXiv:1106.5685



# 3+1 Global Fit to World Neutrino Data Only



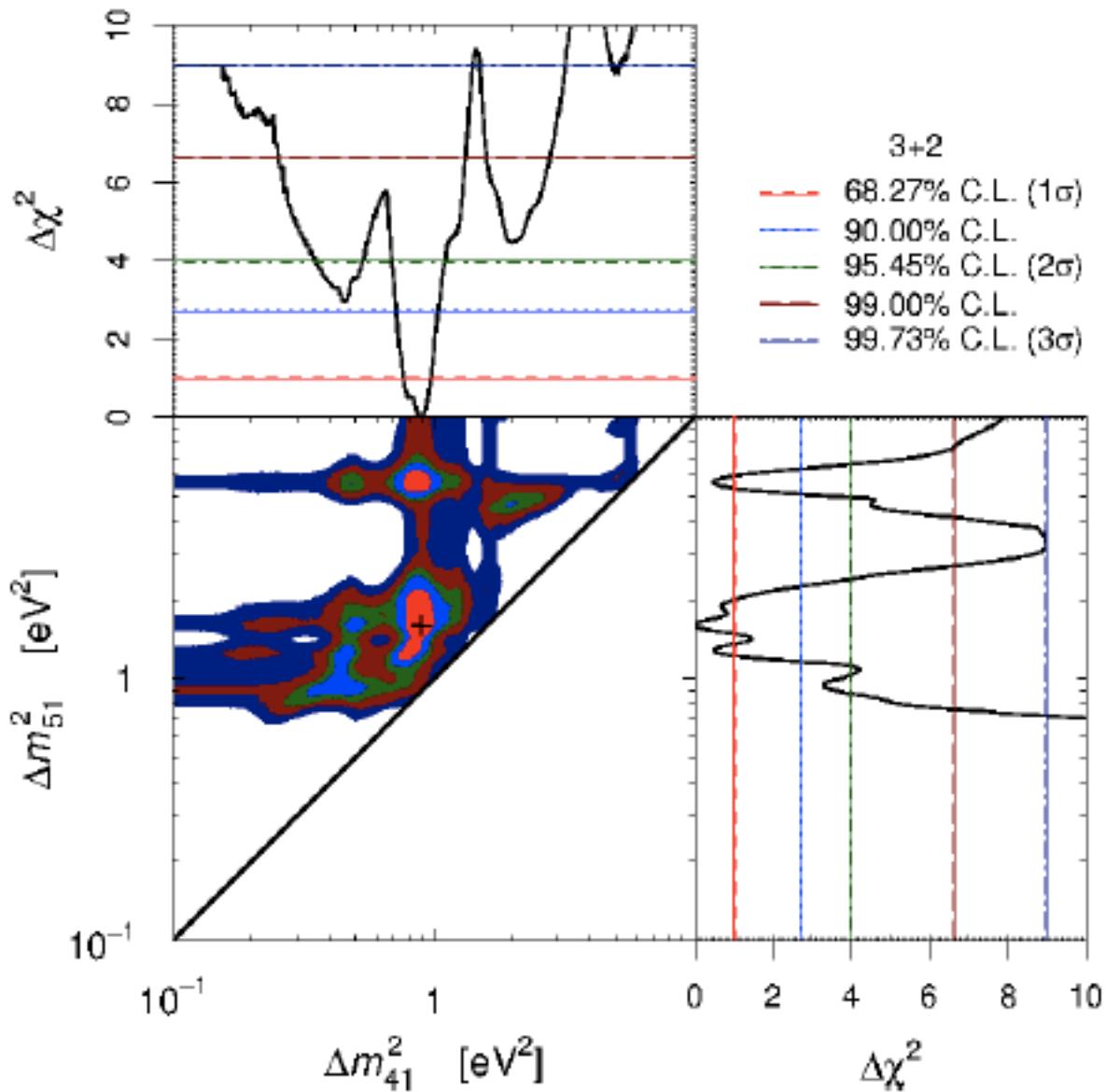
G. Karagiorgi et al.,  
arXiv:0906.1997

**Best 3+1 Fit:**  
 $\Delta m_{41}^2 = 0.19 \text{ eV}^2$   
 $\sin^2 2\theta_{\mu e} = 0.031$   
 $\chi^2 = 90.5/90 \text{ DOF}$   
**Prob.** = 46%

Predicts  $\nu_\mu$  &  $\nu_e$  disappearance of  $\sin^2 2\theta_{\mu\mu} \sim 3.1\%$  and  $\sin^2 2\theta_{ee} \sim 3.4\%$

# Global 3+2 Fit to World Neutrino & Antineutrino Data

Giunti & Laveder, arXiv:1107.1452



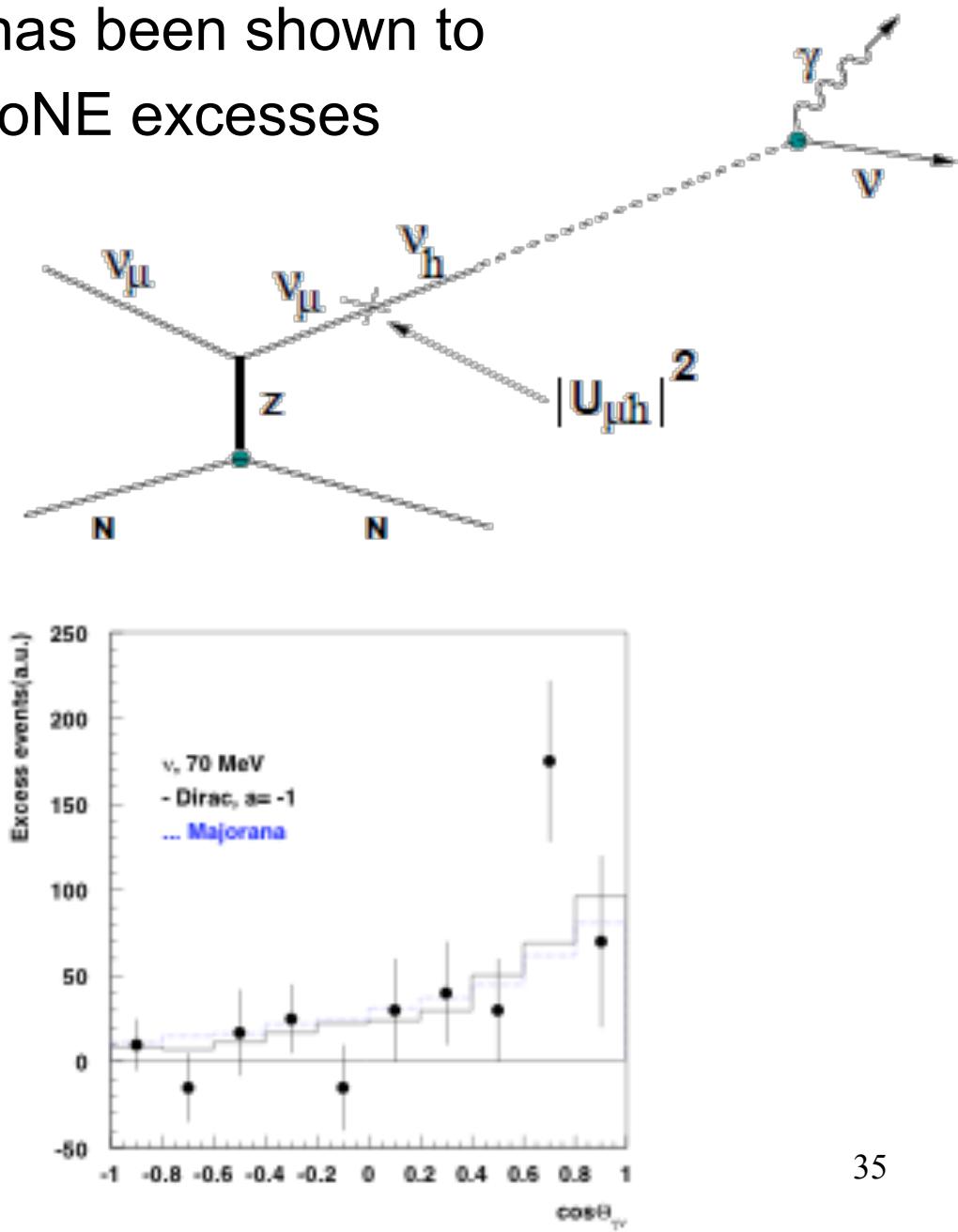
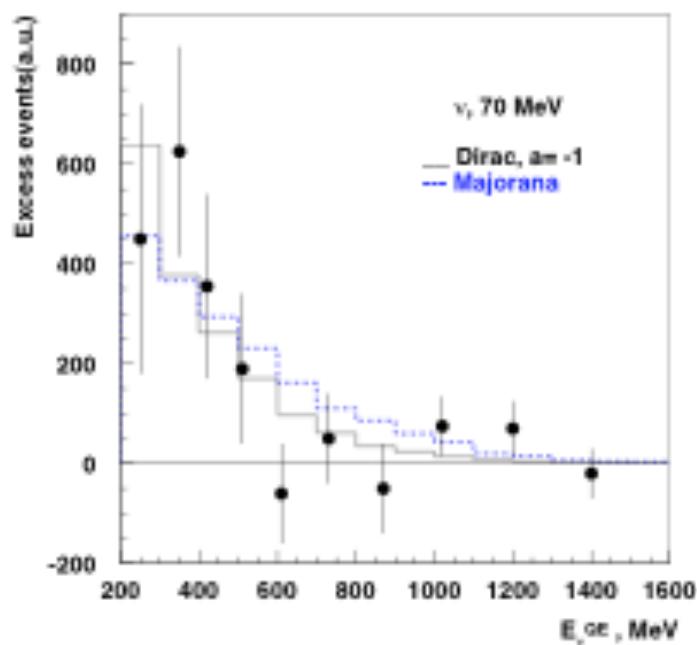
	3+1	3+2
$\chi^2_{\text{min}}$	100.2	91.6
NDF	104	100
GoF	59%	71%
$\Delta m_{41}^2 [\text{eV}^2]$	0.89	0.90
$ U_{e4} ^2$	0.025	0.017
$ U_{\mu 4} ^2$	0.023	0.018
$\Delta m_{51}^2 [\text{eV}^2]$		1.60
$ U_{e5} ^2$		0.017
$ U_{\mu 5} ^2$		0.0064
$\eta$		$1.52\pi$
$\Delta\chi^2_{\text{PG}}$	24.1	22.2
$\text{NDF}_{\text{PG}}$	2	5
PGoF	$6 \times 10^{-6}$	$5 \times 10^{-4}$

However, in 3+2 models  
there is some tension  
between neutrino & antineutrino  
data.

# Sterile $\nu$ Decay?

- The decay of a  $\sim 50$  MeV sterile  $\nu$  has been shown to accommodate the LSND & MiniBooNE excesses
  - Gninenko, PRL 103, 241802 (2009)

arXiv:1009.5536



## Future L/E~1 Experiments

# IceCube Atmospheric Neutrino Angular Distribution

arXiv:1010.3980 (40 strings; 12 months of data)

**IceCube covers the range of  $0.001 < L/E < 100$  m/MeV !**

+ Matter  
Effects can  
enhance  
Oscillations

70% neutrino +  
30% antineutrino

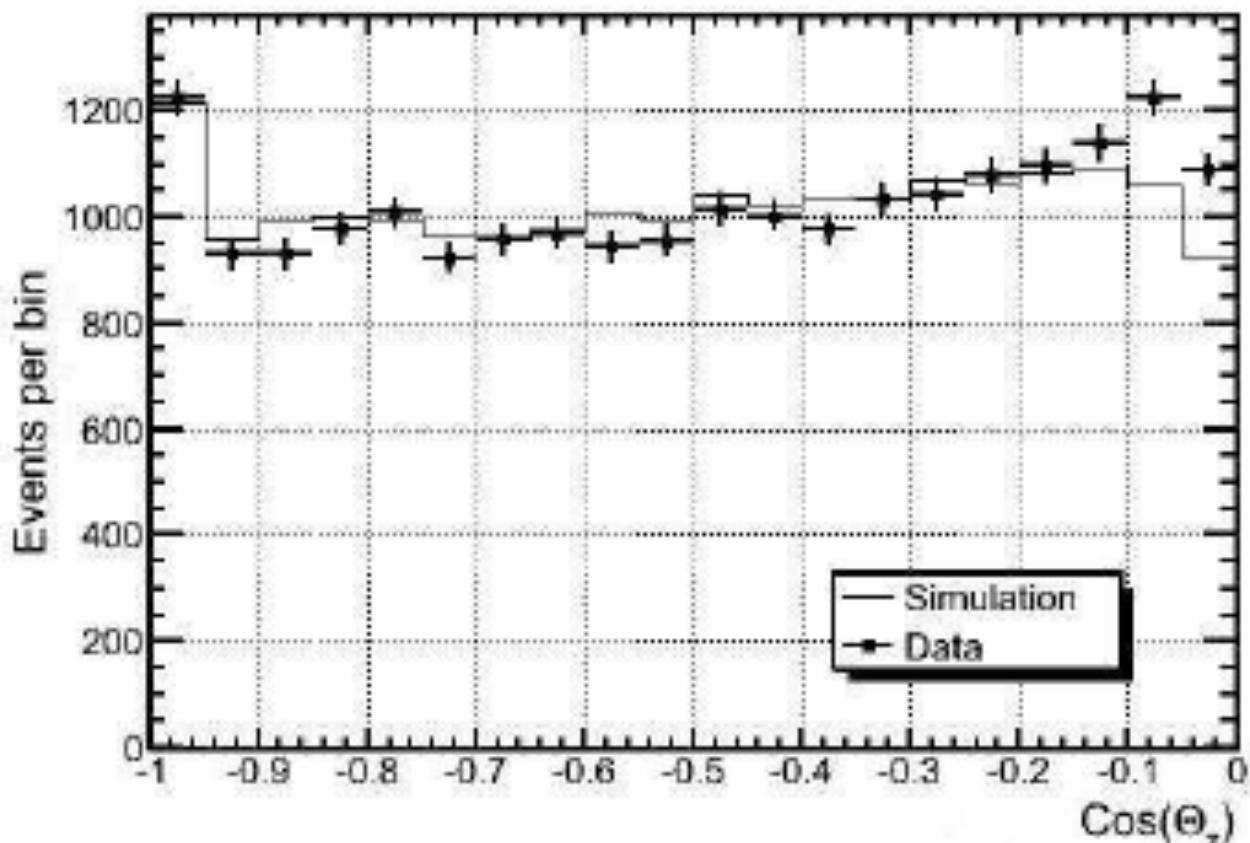


FIG. 19:  $\text{Cosine}(\theta_Z)$  distributions for data and for simulation, using zenith angle from the MPE fit. Simulation has been normalized to the data. Error bars for data are statistical only.

# Future Experiments

- Continue taking MiniBooNE  $\bar{\nu}$  Data (15E20 POT)
  - Combined neutrino and antineutrino appearance analysis.
  - SciBooNE/MiniBooNE  $\bar{\nu}_\mu$  disappearance.
- MicroBooNE (LAr) under construction and will address MB neutrino low energy excess (is it photons or electrons?)
- Borexino is planning a source measurement.
- Few ideas under consideration:
  - Build a MiniBooNE like near detector (LOI arXiv:0910.2698)
  - A second NoVA near detector.
  - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)
  - Redoing a stopped pion source at ORNL (OscSNS - <http://physics.calumet.purdue.edu/~oscsns/>)
  - Project X (high powered proton source at FNAL) would significantly increase neutrino rates.

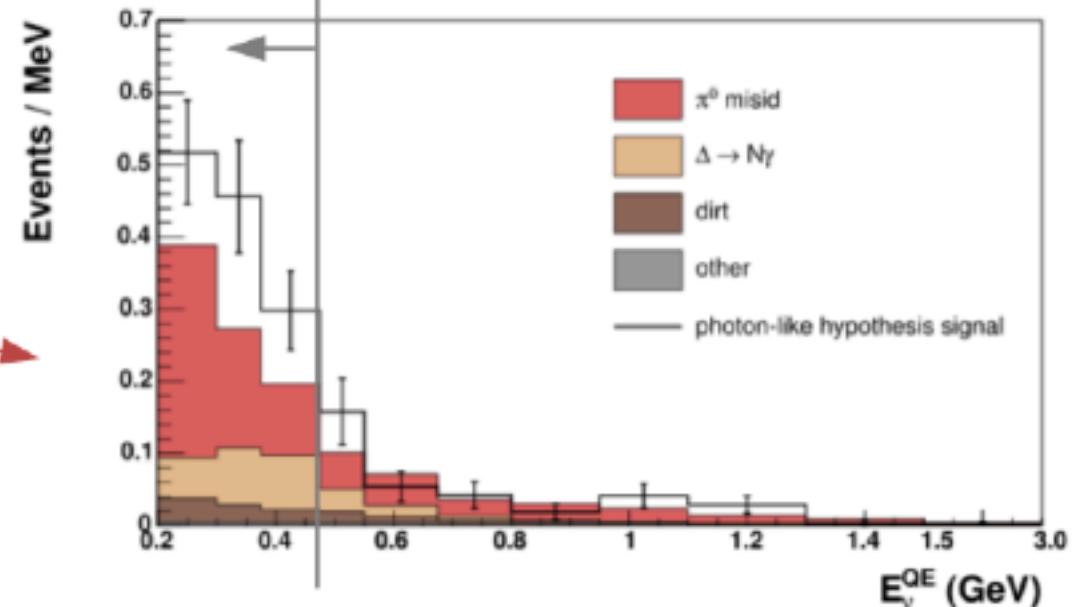
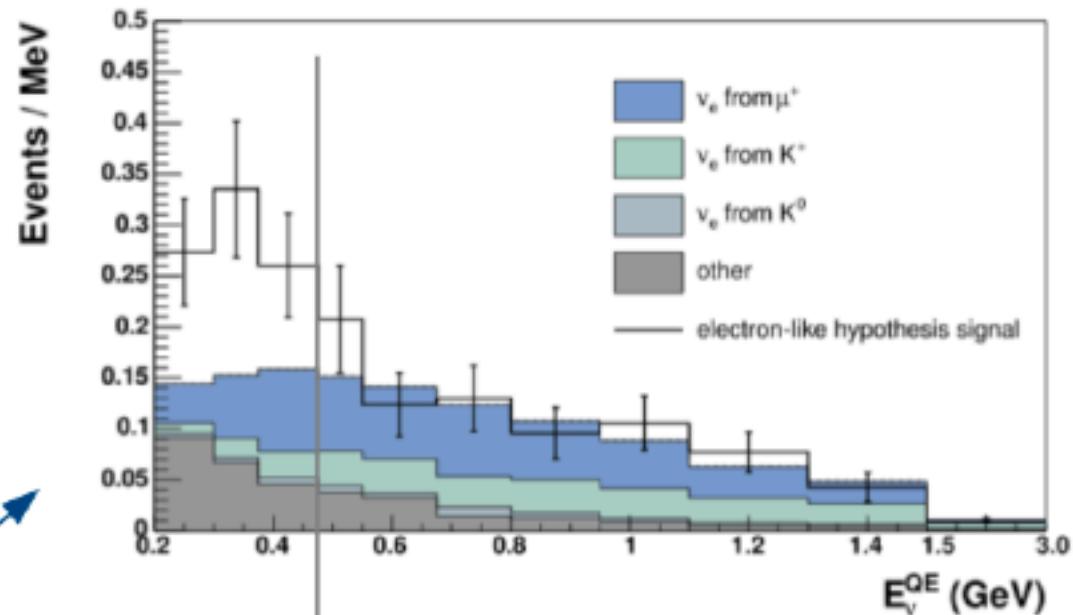
# MicroBooNE at 470m on the BNB

**MicroBooNE sensitivity to low energy excess:**

(neutrino running,  
70 ton fiducial volume,  
x2 higher PID efficiency  
than MiniBooNE,  
3% mis-ID,  
 $6.0 \times 10^{20}$  POT)

**Electron-like hypothesis:**  
36.8 excess events  
41.6 background events  
5.7 $\sigma$  stat. significance

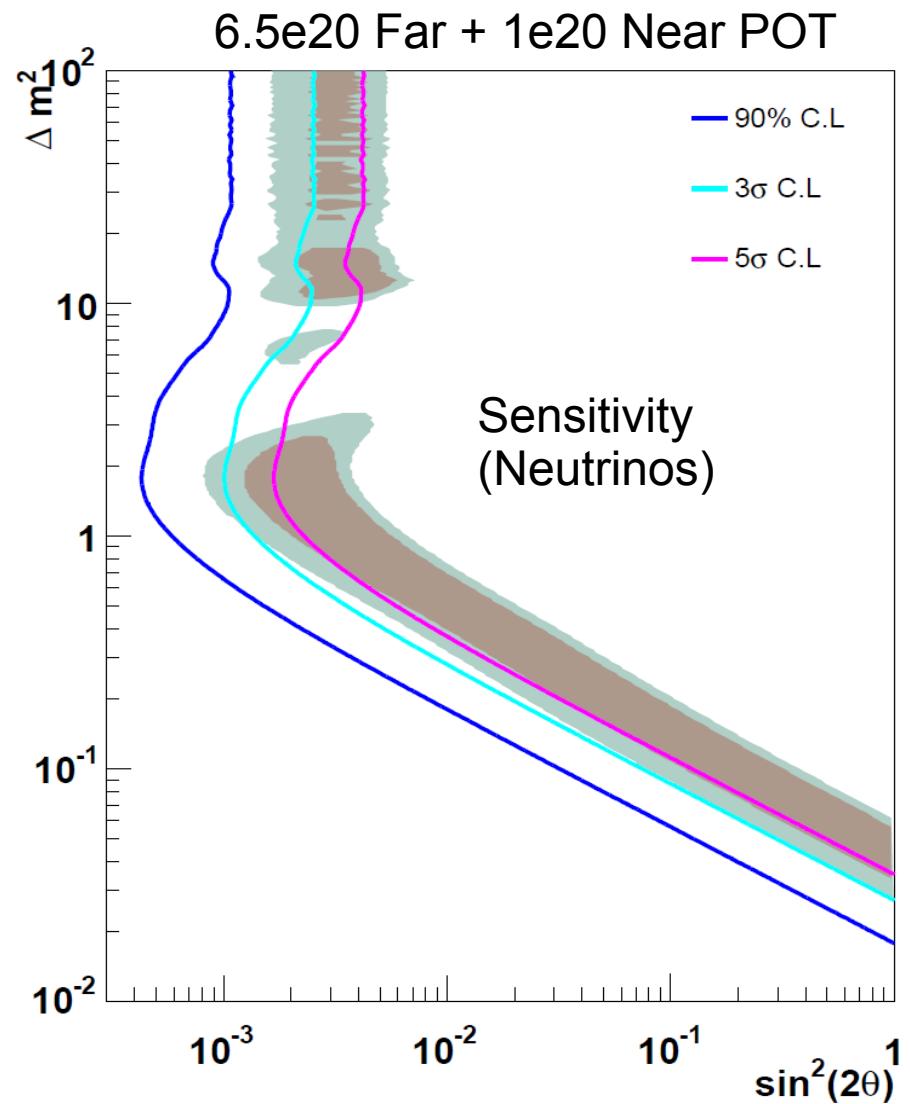
**Photon-like hypothesis:**  
36.8 excess events  
78.9 background events  
4.1 $\sigma$  stat. significance



- LOI in the works to propose a second large LAr detector on the BNB

# BooNE (a near detector for MiniBooNE)

- Build a MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure  $\nu_\mu \rightarrow \nu_e$  &  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations and CP violation

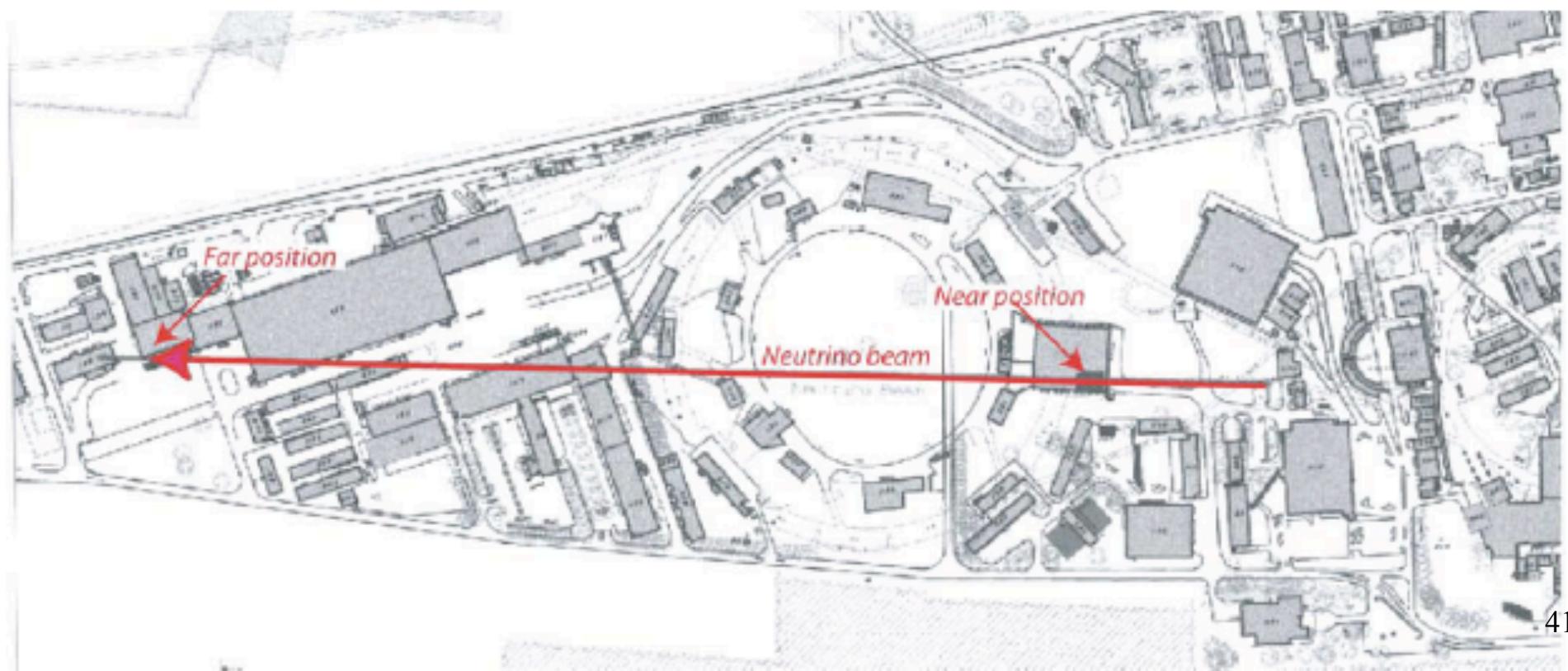


# ICARUS at the CERN PS (Plan B)

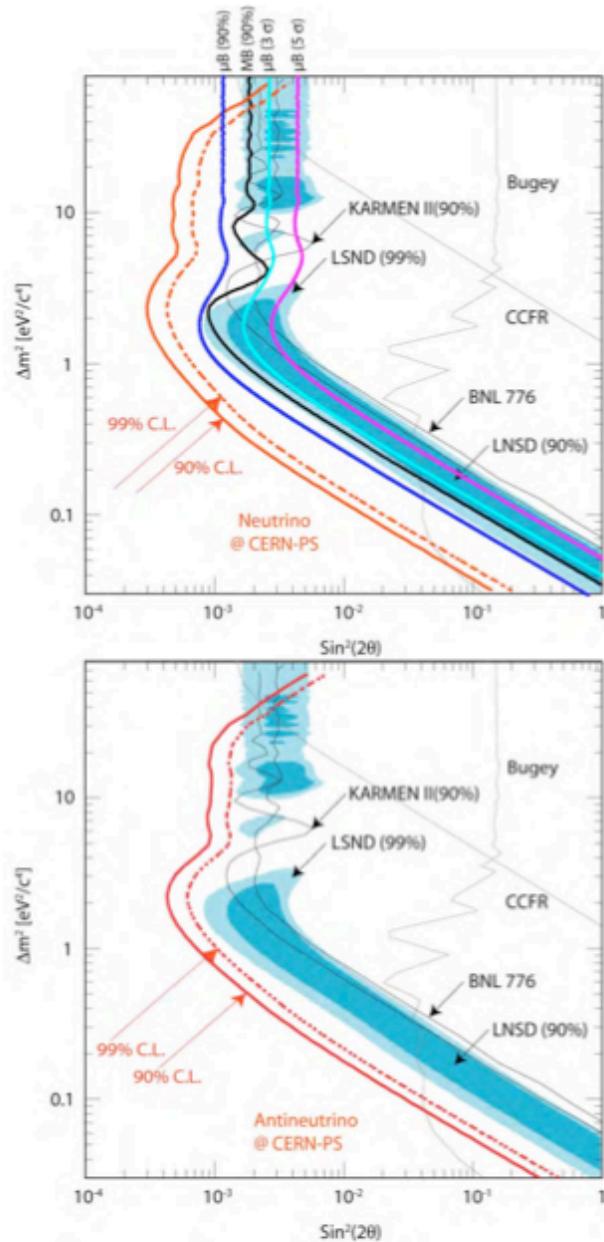
## A new search for anomalous neutrino oscillations at the CERN-PS

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B. Baibussinov<sup>a</sup>, E. Calligarich<sup>b</sup> S. Centro<sup>a</sup>, D. Gibin<sup>a</sup>, A. Guglielmi<sup>a</sup>,  
F. Pietropaolo<sup>a</sup>, C. Rubbia<sup>c,\*</sup> and P. Sala<sup>d</sup>



# ICARUS at the CERN PS



**Figure 25.** Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (top) and anti-neutrino (bottom) for  $2.5 \times 10^{29}$  pot and  $5.0 \times 10^{29}$  pot respectively. The LSND allowed region is fully explored in both cases.



**Figure 7.** The ICARUS T600 detector installed in Hall B at LNGS.

600 ton ICARUS at 850 m

150 ton LAr at 127 m

# OscSNS

- Spallation neutron source at ORNL
- 1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos
- Can repeat the LSND measurement at ~5 sigma in one year!



# Project X (~MW proton source) at FNAL

- Design/build a series of experiments with Project X to explore in detail the source of new physics:
  - DIF (300-600kW at 3GeV with a new accumulator)
    - 15-30 times more flux with reduced Kaon background.
  - DIF (25-50kW at 8GeV with antiproton accumulator) directly into BNB.
  - DAR difficult due to long duty cycle.
  - Beam dump exotics - axions, paraphotons, etc.
  - Cross sections.

# Conclusions

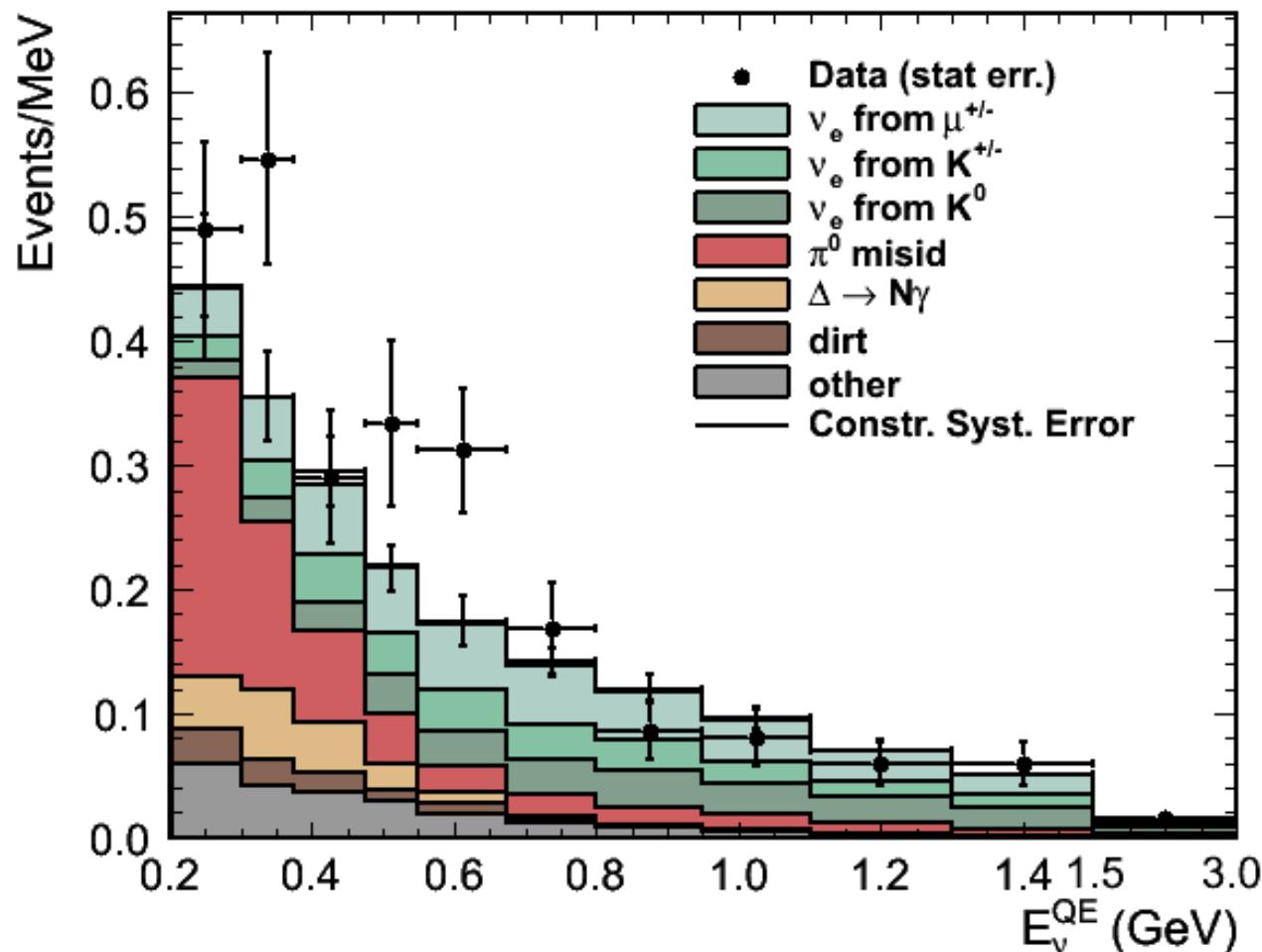
- The MiniBooNE data are consistent with  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations at  $\Delta m^2 \sim 1 \text{ eV}^2$  and consistent with the evidence for antineutrino oscillations from LSND.
- The MiniBooNE  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillation allowed region appears to be different from the  $\nu_\mu \rightarrow \nu_e$  oscillation allowed region. (Can nuclear effects possibly explain this difference?)
- Mounting evidence from various experiments at  $L/E \sim 1$  that there is maybe more to oscillations than the standard three active neutrino model.
- Still no smoking gun for new physics at  $L/E \sim 1$ . However, a new crop of experiments under construction or proposed could measure neutrino oscillations with high significance ( $>5\sigma$ ) and potentially prove that there is new physics at the  $\Delta m^2 \sim 1 \text{ eV}^2$  scale.

# Backup

# MiniBooNE Antineutrino Oscillation Results

A. A. Aguilar-Arevalo, Phys. Rev. Lett. 105, 181801 (2010)

- 5.66e20 POT



# LSND $\bar{\nu}_e$ Background Estimates

Estimate	$\bar{\nu}_e/\bar{\nu}_\mu$	$\bar{\nu}_e$ Bkgd	LSND Excess
LSND Paper	0.086%	19.5+-3.9	87.9+-22.4+-6.0
Zhemchugov Poster1	0.071%	16.1+-3.2	91.3+-22.4+-5.6
Zhemchugov Poster2	0.092%	20.9+-4.2	86.5+-22.4+-6.2
Zhemchugov Seminar	0.119%	27.0+-5.4	80.4+-22.4+-7.1

All  $\bar{\nu}_e$  background estimates assume a 20% error. Note that the  $\bar{\nu}_e/\bar{\nu}_\mu$  ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses **MCNP**)

Zhemchugov Poster1: **FLUKA**  $\bar{\nu}_e/\bar{\nu}_\mu$  ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Poster2: **GEANT4**  $\bar{\nu}_e/\bar{\nu}_\mu$  ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Seminar: **FLUKA**  $\bar{\nu}_e/\bar{\nu}_\mu$  ratio presented at CERN on September 14, 2010

Although the analysis of Zhemchugov et al. is not fully understood or endorsed, their  $\bar{\nu}_e/\bar{\nu}_\mu$  ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of  $\bar{\nu}_\mu$  p  $\rightarrow$   $\mu^+$  n interactions, which confirms the  $\pi^-$  production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!

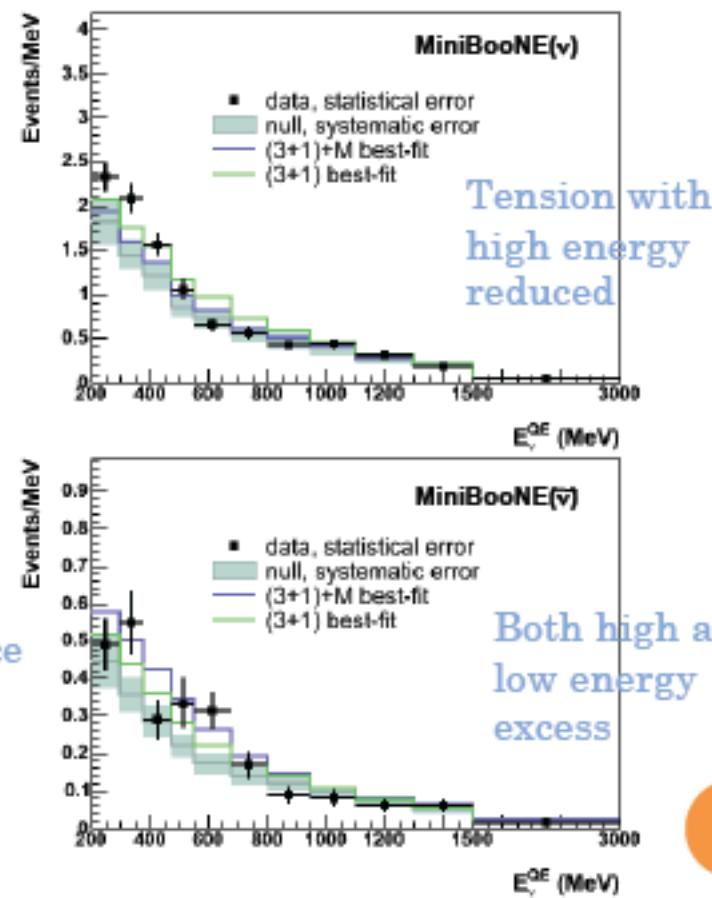
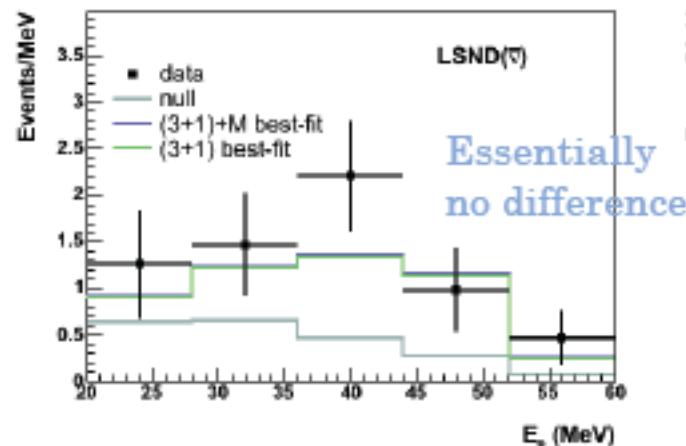
# Fit With Non-Standard Matter-Like Effects

## Georgia Karagiorgi (DPF)

### FIT RESULTS: BEST-FIT DISTRIBUTIONS

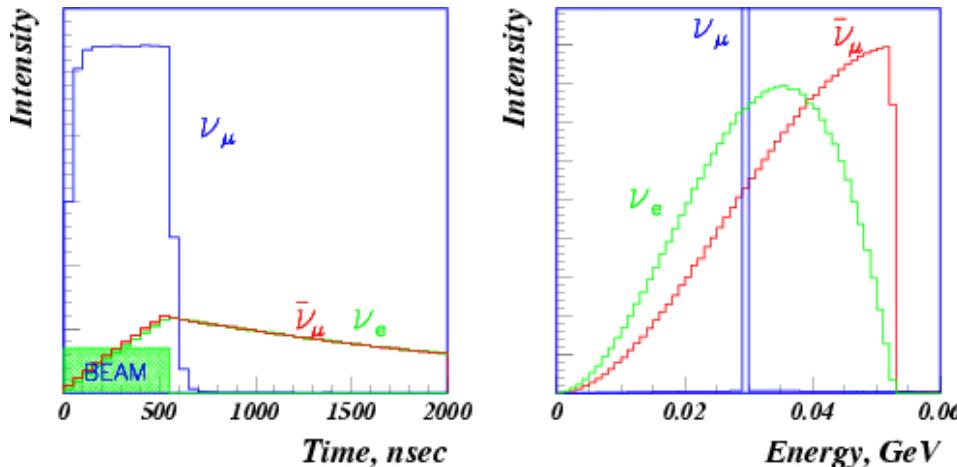
$$\begin{aligned}\chi^2 (3+1)+M &= 44.5/38 (22\%) \\ \chi^2 (3+1) &= 52.9/39 (7\%) \\ \Delta\chi^2/\text{dof} &= 8.5/1 \text{ fit param.}\end{aligned}$$

Compatibility increases  
from 2.3% to 17.4%.



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# OscSNS



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$   $\Delta(L/E) \sim 3\%$  ;  $\nu_e p \rightarrow e^+ n$

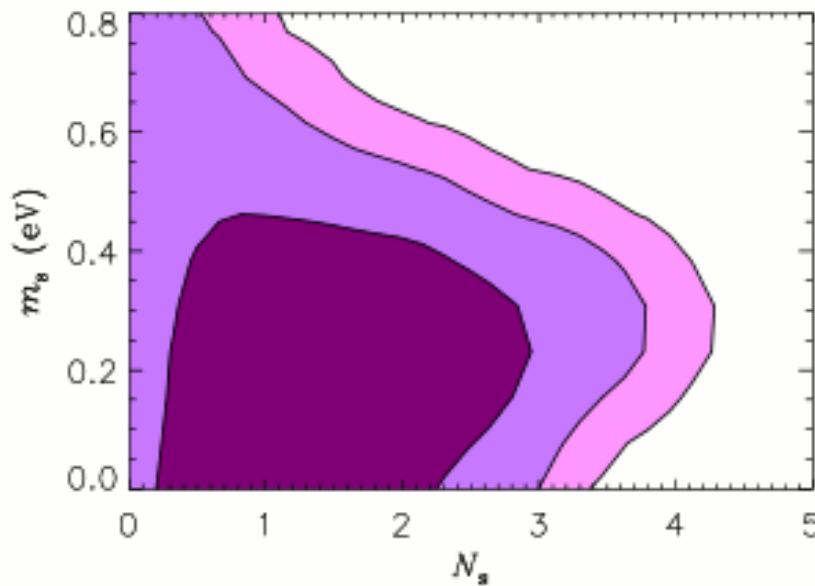
$\nu_\mu \rightarrow \nu_e$   $\Delta(L/E) \sim 3\%$  ;  $\nu_e C \rightarrow e^+ N_{gs}$

$\nu_\mu \rightarrow \nu_s$   $\Delta(L/E) < 1\%$  ; **Monoenergetic  $\nu_\mu$ !**;  $\nu_\mu C \rightarrow \nu_\mu C^*(15.11)$

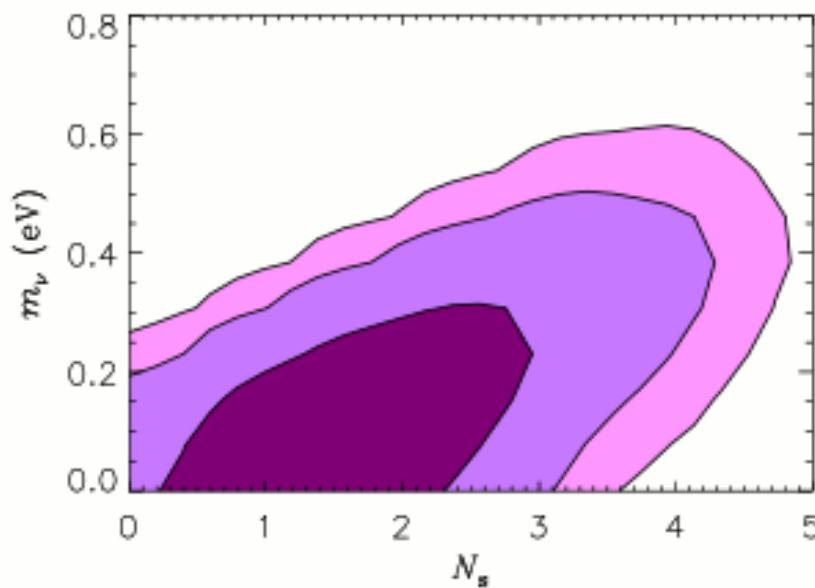
$\bar{\nu}_\mu \rightarrow \bar{\nu}_s$  ;  $\nu_\mu C \rightarrow \nu_\mu C^*(15.11)$

OscSNS would be capable of making precision measurements of  $\bar{\nu}_e$  appearance &  $\nu_\mu$  disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)).

# Cosmology Data Consistent with Extra Sterile Neutrinos (J. Hamann, et. al. arXiv:1006.5276)



$$3 + N_s \\ m_\nu = 0$$



$$3 + N_s \\ m_s = 0$$